AIR PHOTO INTERPRETATION

OF

GREAT LAKES ICE FEATURES

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ABSTRACT

The report collects visual imagery of ice features and patterns common to the Great Lakes and gives interpretations of it. The study is based on USAF aerial photography flown over the Great Lakes on March 23, 1963 together with observations and photographs taken on U. S. Coast Guard ice reconnaissance flights during January and February 1965. Ice features are included from all Great Lakes with the majority from Lake Erie.

The photographs and interpretations are arranged according to features found in open water areas during freeze-up, in the newly formed ice, in winter ice and in patterns resulting from snow and wind.

The report brings out the role of snow and water turbulence in determining the types of ice sheet formed.

Recommendations are made for future research.

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INTRODUCTION

Limited information is available in the literature on visual imagery of Great Lakes ice conditions. This report collects some of the basic imagery of ice features and patterns common to the Great Lakes and provides a description and interpretation of them.

This report is based principally on aerial photography flown by the U. S. Air Force on March 23, 1963. The mission included a centerline flight down all five of the Great Lakes and resulted in vertical photographs (Scale 1:22,000) and a complex array of low and high angle obliques.

The interpretation of these ice features was aided by observations and photographs made by the writer on five ice reconnaissance flights in January and February 1965 and by previous lake ice studies in Michigan, northern Canada, Greenland, and the Arctic Ocean.

Photographs of ice features from all of the Great Lakes were used in the report; however, the majority are from Lake Erie, where the flight line covered maximum ice concentrations and a wide variety of features. The illustrations used consist of enlarged sections from the aerial photographs, low level photographs taken on the ice reconnaissance flights, and ground photography.

The imagery of Great Lakes ice conditions is complex, for ice formation and physical break-up of the ice sheet goes on throughout the winter. This is in contrast to ice conditions on inland lakes where the successive stages of ice formation, accretion and break-up are well defined. The product of physical break-up (brash) is constantly fed back into the ice formation cycle where it is refrozen into floes which may then recycle, or the brash may accumulate in shore zones and freeze as fast ice or as part of the icefoot.

There is a wide range in the meteorological conditions affecting ice formation in the 7 1/2 degree latitude span of the Great Lakes, however, there are ice patterns and features which are common to all of the lakes. Photographs representative of these features have been grouped together according to the features observed in open waters during freeze-up, in newly formed ice skims, in older and thicker ice, and surface features caused by snow and wind. The photograph locations are keyed by figure number to the Great Lakes map in Figure 1.

This study was made during the period January 11, 1965 - May 24, 1965 in the Great Lakes Research Division, Institute of Science and Technology, The University of Michigan.

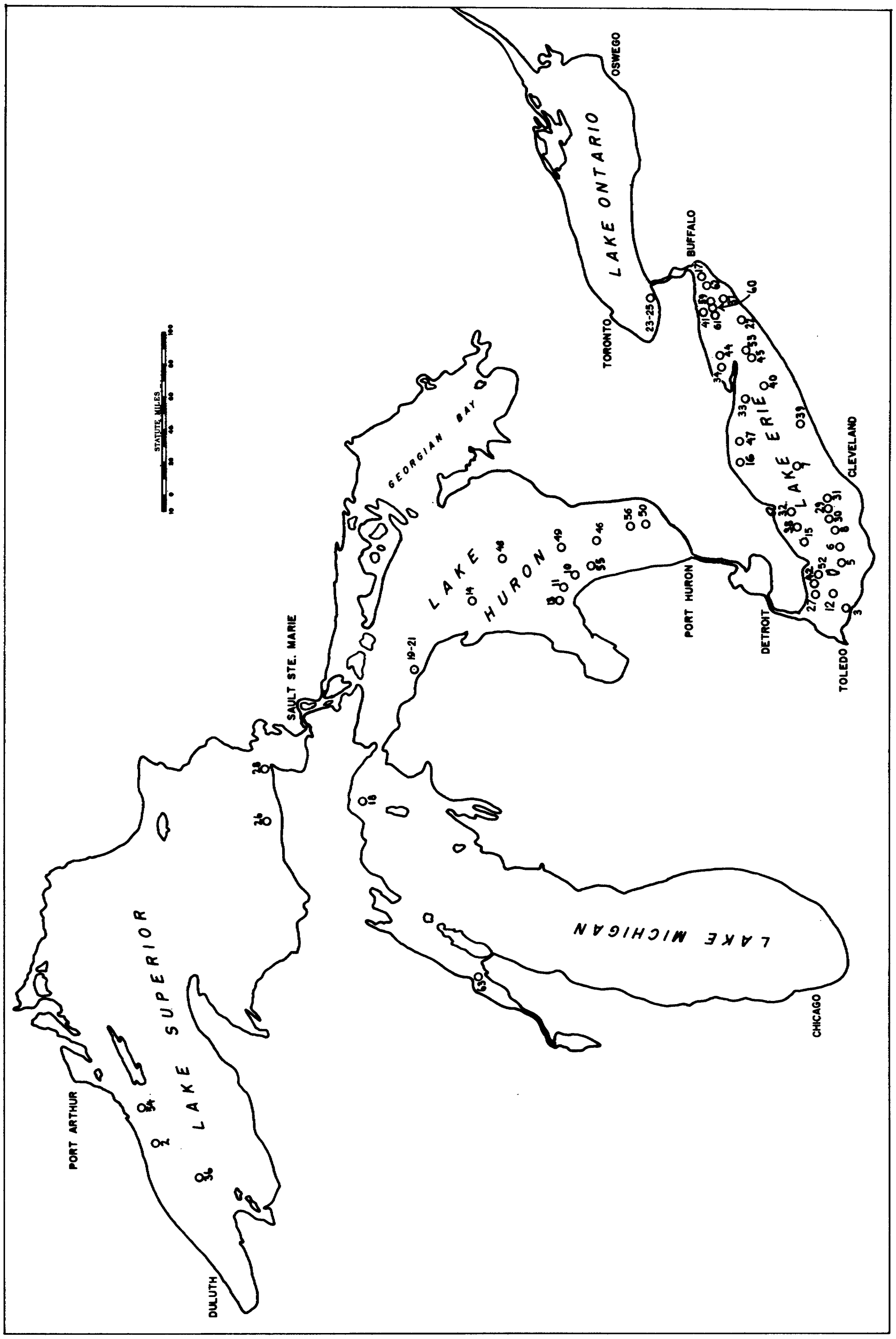

FIG. 1. LOCATION MAP OF GREAT LAKES ICE PHOTOGRAPHS

FEATURES IN OPEN WATER AREAS DURING FREEZE-UP

This section of the report illustrates freeze-up features found in areas of open water. Since the Great Lakes seldom freeze over completely, these features may be observed at any time during the winter.

When cold air masses move across the relatively warm lake water, masses of fog called frost smoke (Fig. 2) rise from the water surface. Later in the winter when leads open up in the ice sheet, curtains of frost smoke rise along these breaks in the ice cover.

Distinctive patterns form on the water surface both from the action of wind (Fig. 3) and from the formation of frazil ice. As the water surface becomes supercooled, small centers of crystallization form on the water surface. These consist of small ice crystals in the form of discoids and spicules. Dendritic growths extend out from these centers of crystallization so that the water surface is covered with a loose mass of dendritic plates called frazil ice (Fig. 4). Under conditions of quiet water, these plates extend over the water surface and form an ice skim a few millimeters in thickness. If quiet water conditions persist, a normal ice sheet begins to accrete under this frazil ice skim.

Under moderate wind conditions the frazil ice is able to form over large areas to produce drifting patches which appear as smooth water. These frazil ice patches are very similar in appearance to the pattern produced by an oil slick.

In the turbulent waters of the Great Lakes, these loose, thin frazil ice crystals collect into streaks under the influence of the wind and gradually freeze together in long narrow ice skims (see Figs. 5, 6, 7). Frazil ice gradually forms on the intervening water areas to form a complete ice skim.

The effects of ground swells and wind produces long fractures and tears in this thin ice skim (Fig. 8). Heavy snows often blanket the water areas between these fragments of frazil ice skim while wind-blown snow catches in the smaller fractures and tears (Fig. 9). Wind-blown snows which collect along the fractures form linear trends of snow ice patches (Figs. 10, 11).

Strong winds blowing across a frazil ice skim can create triangular shaped blowouts similar to those seen in Figure 12. These relict patterns formed during the period of initial freeze-up remain with ice sheet throughout the winter.

Slush layers form on the water surface as a result of snowfalls. In the case of thick slush layers, winds can shear the layers to produce a unique pattern (Fig. 13). The wind can open up areas in the thin slush layer as well as produce folded or stirred patterns (Figs. 14, 15). These slush patterns become part of the ice sheet and reflect the history of the period of early ice formation (Fig. 16).

Pancake ice results from the break-up of ice sheets and the abrasion of the fragments together with the accretion of slush and frazil ice. Figures 17 and 18 indicate the types of pancake ice which were frequently observed, on flights during January-February 1965.

Ball ice consists of roughly spherical masses of slush and frazil ice which accrete in the turbulent waters of nearshore and offshore conditions (Figs. 19-25).

The icefoot consists of an ice barrier which forms along the shoreline and is composed of frozen masses of spray, brash ice, and ice cakes. Figures 26-28 illustrate several types of icefoot observed on Lakes Superior and Erie.

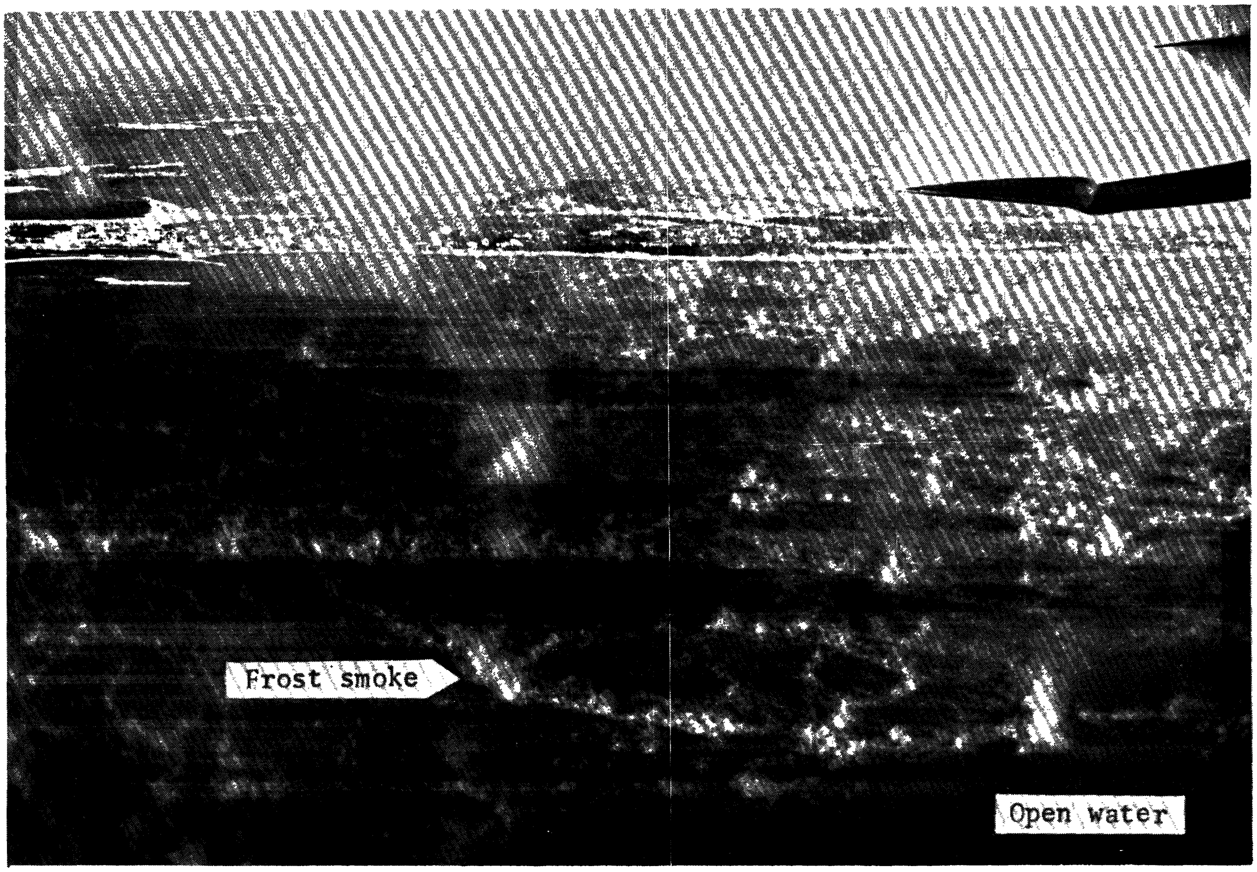

FIG. 2. FROST SMOKE. Frost smoke rising from the water surface. The fog rises from the relatively warm water surface when it is exposed to an air temperture much below freezing. If there is a strong wind blowing no fog is produced, for the vapor is distributed by the accompanying turbulence through too large a volume of air to produce saturation. In this case the frost smoke rises with a cellular pattern from the water surface. Lake Superior, 1/28/65.*
Altitude: 2500 ft.

*January 28, 1965.

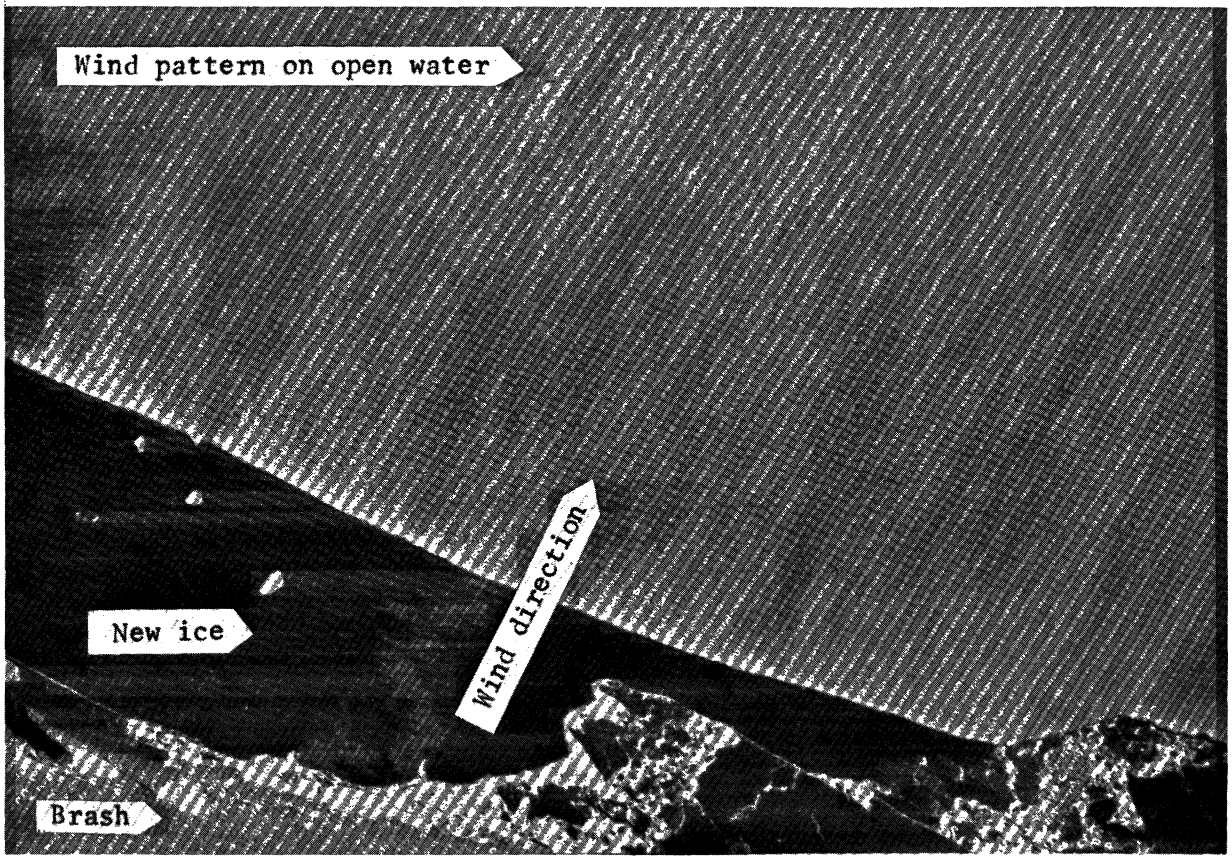

FIG. 3. WIND PATTERN ON OPEN WATER. The pattern of wind streaks on open water is illustrated to contrast with the pattern which appears when frazil ice begins to form on the water surface. The differences in gray tone in the plume-like forms reflect sudden changes in wind velocity and direction. Lake Erie, Photo 9L-47-1R.

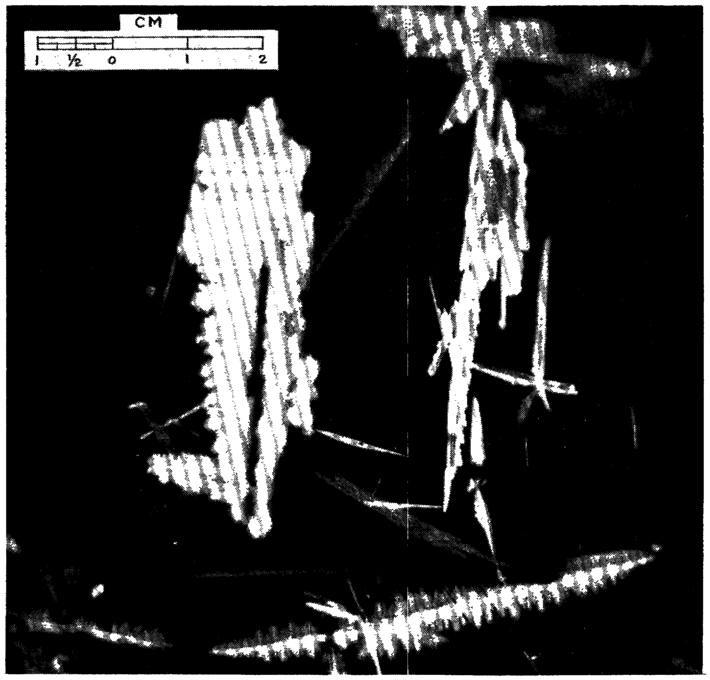

FIG. 4. FRAZIL ICE CRYSTALS. The first ice which forms on the supercooled water surface consists of needle-like crystals fringed by dendritic growths as well as hexagonal crystals with snowflake-like form. The growth of these dendrites extends over the water surface to form an ice "skim" consisting of a loose felted mesh of crystals a few millimeters in thickness. The water surface takes on a slick appearance as it becomes covered with frazil ice. These crystals formed in a crystallizing dish and were photographed between crossed polaroid filters.

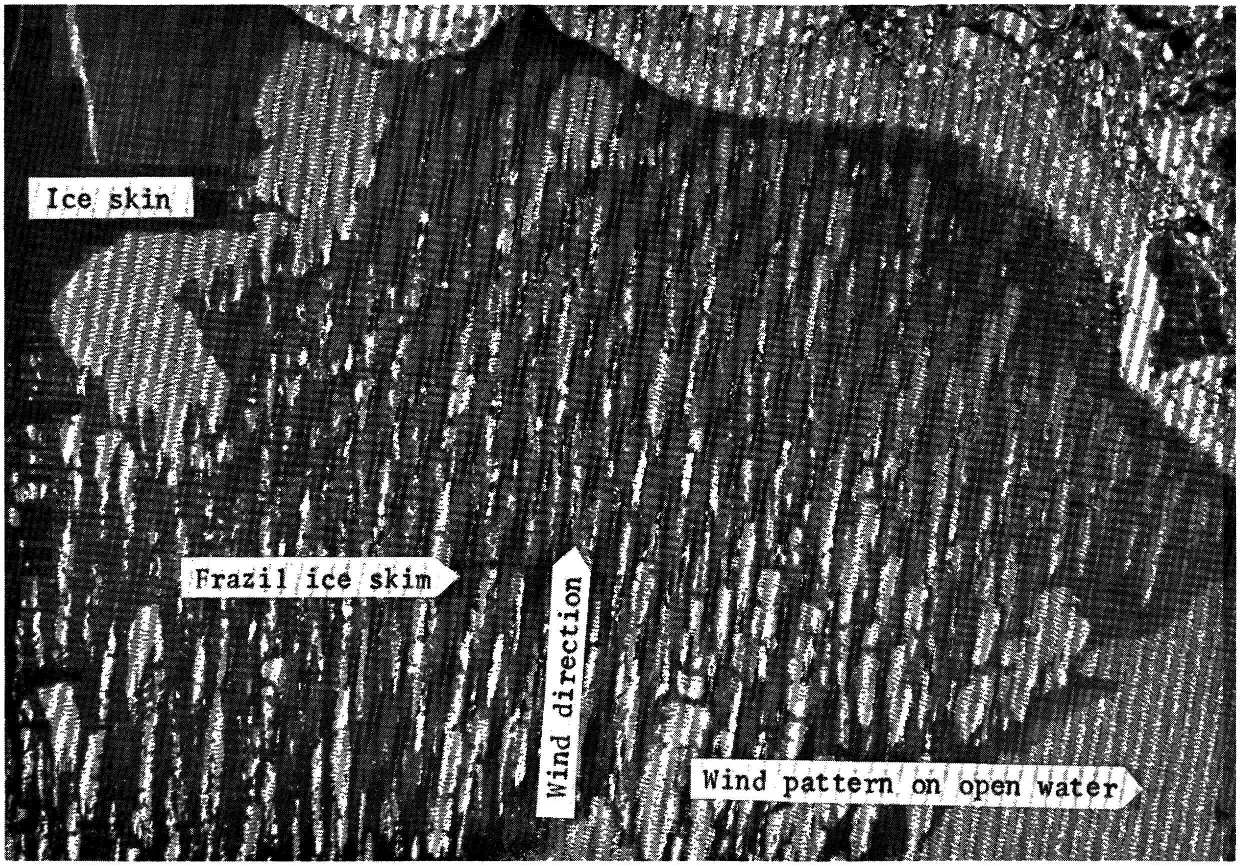

FIG. 5. FRAZIL ICE AND WIND PATTERNS. The light gray pattern indicates areas of open water rippled by the wind while the darker gray is frazil ice in the process of consolidation. In the upper left the frazil ice has consolidated to form an ice "skin" which is hard enough to be sheared by the movement of the adjoining ice floes. The frazil ice skim is estimated at several millimeters. Lake Erie, Photo 9L-107-1R.

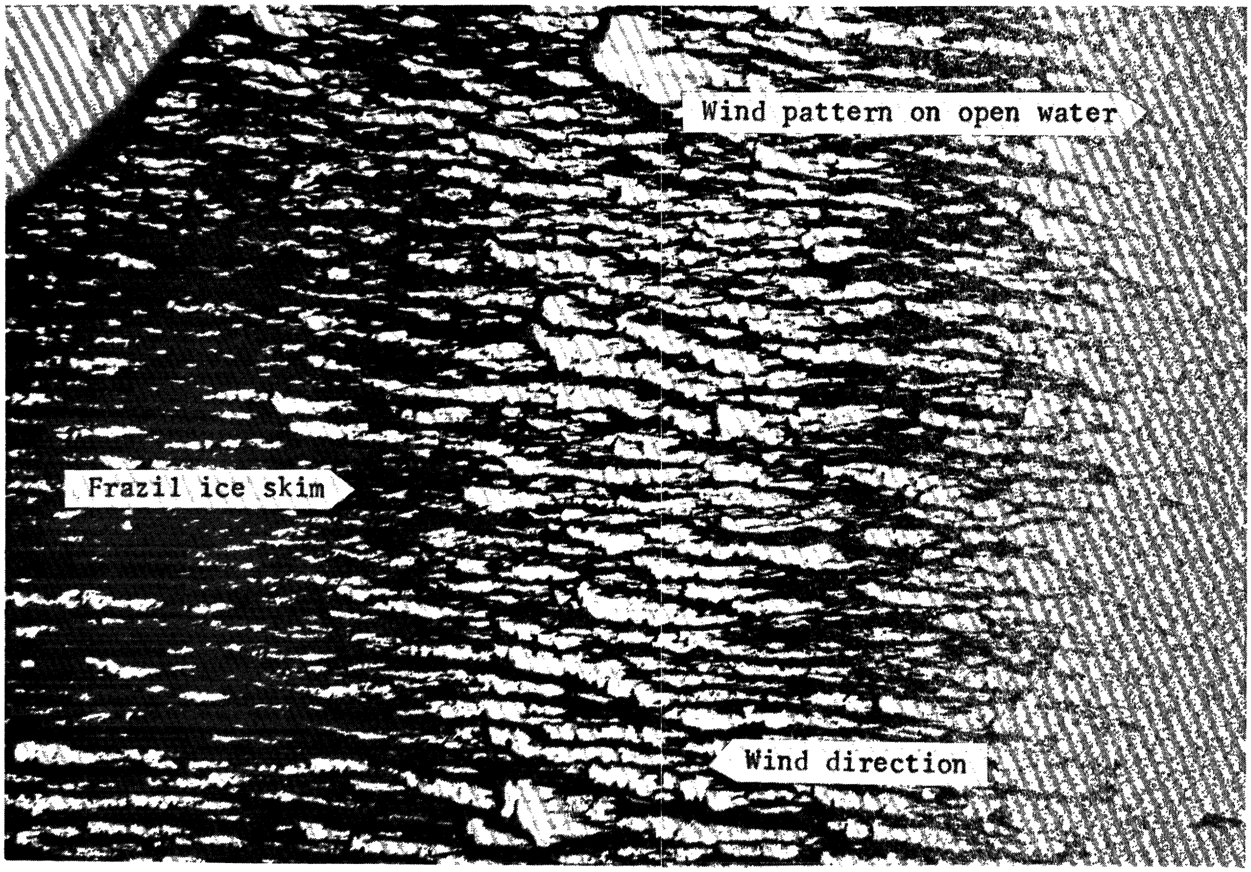

FIG. 6. FORMATION OF A FRAZIL ICE SKIM. The formation of a frazil ice skim can be traced from the rippled pattern of open water on the right through streaks of frazil ice to the nearly complete ice skim at the left. Lake Erie, Photo 9R-112-1R.

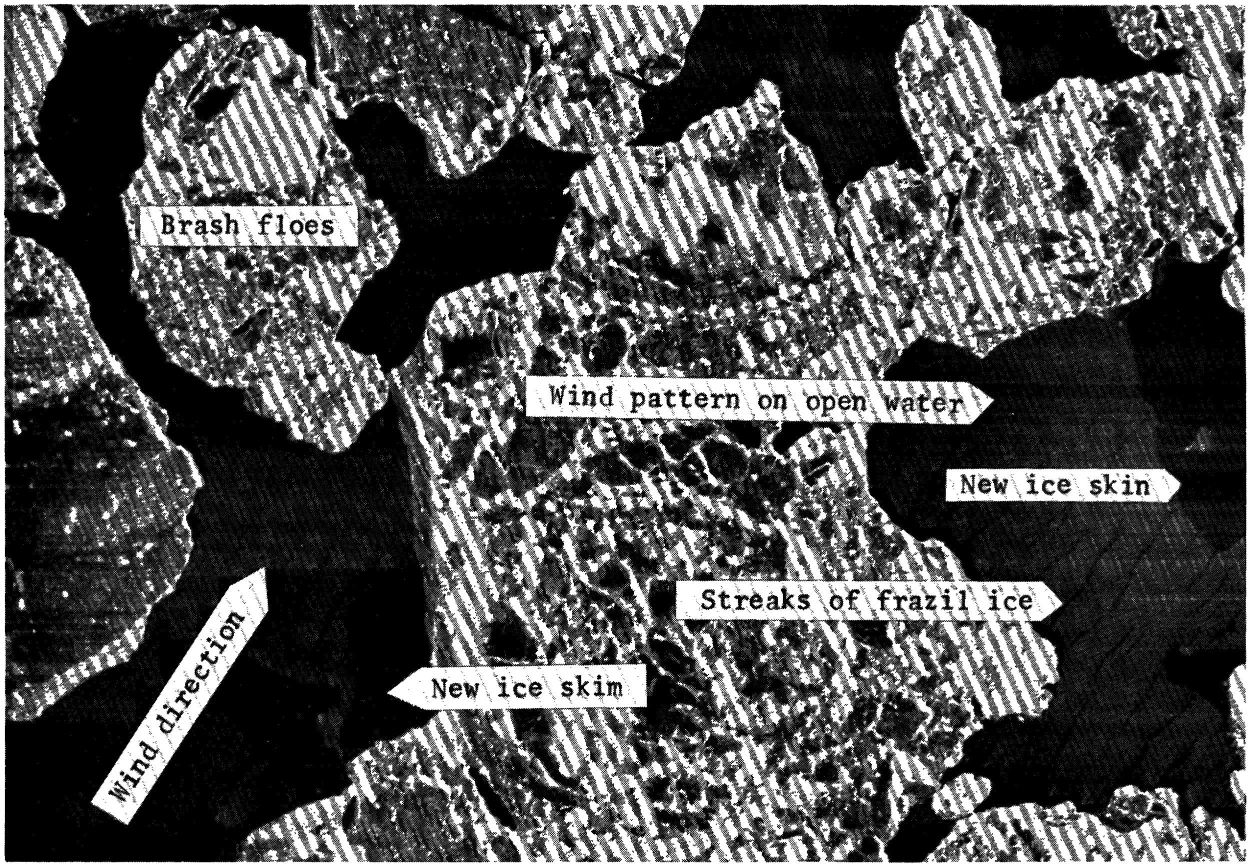

FIG. 7. STREAKS OF FRAZIL ICE, NEW ICE SKIN, AND WIND PATTERNS. The dark-toned areas are streaks of frazil ice crystals and newly formed ice skin while the rippled gray areas are open water. Indications of wind direction are provided by the streaks of frazil ice which stream from the leeward side of an ice floe and extend into the open water. Lake Erie, Photo 9L-212-1R.

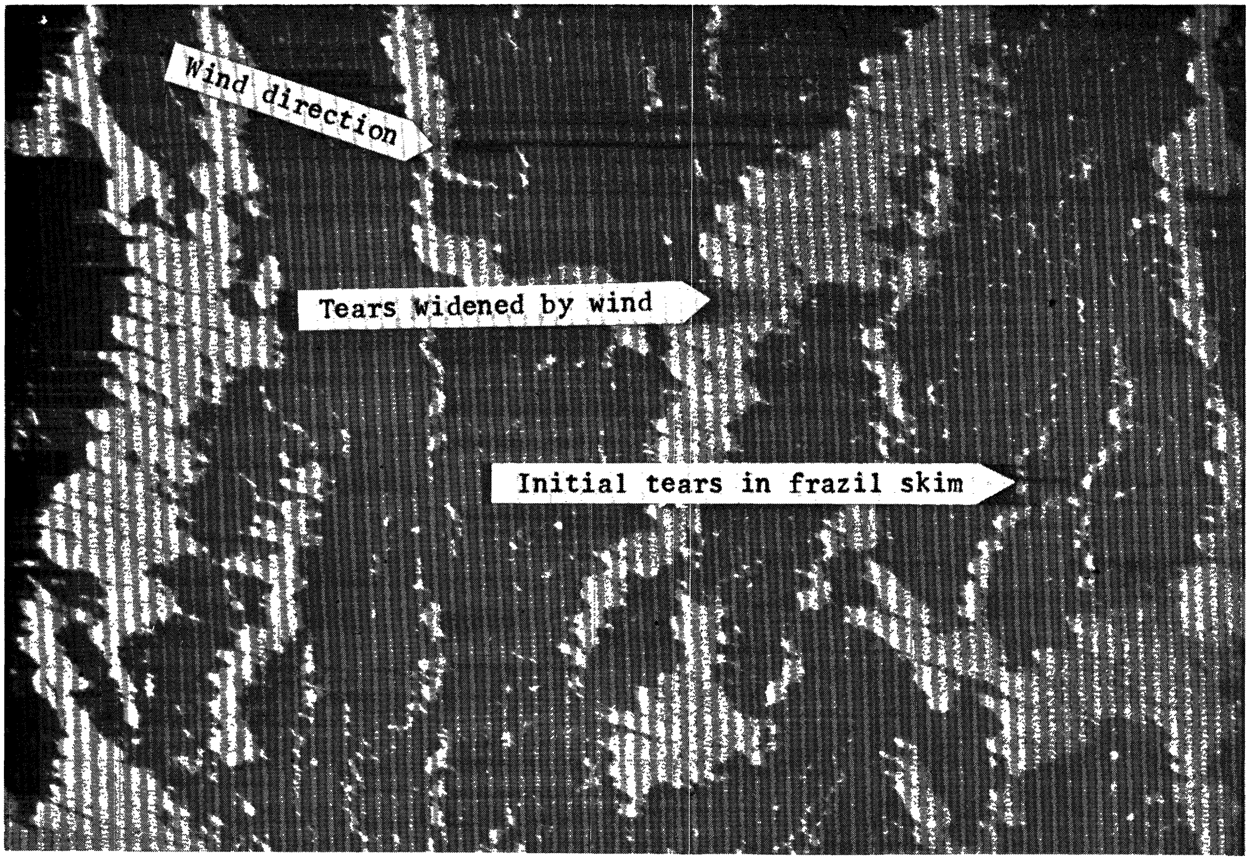

FIG. 8. EFFECTS OF WIND ON A FRAZIL ICE SKIM. This illustrates a frazil ice skim in the process of being torn apart by wind action. Frazil ice streaks form on the open water between fragments while new tear lines form within the skin. Lake Erie, Photo 9L-127-1R.

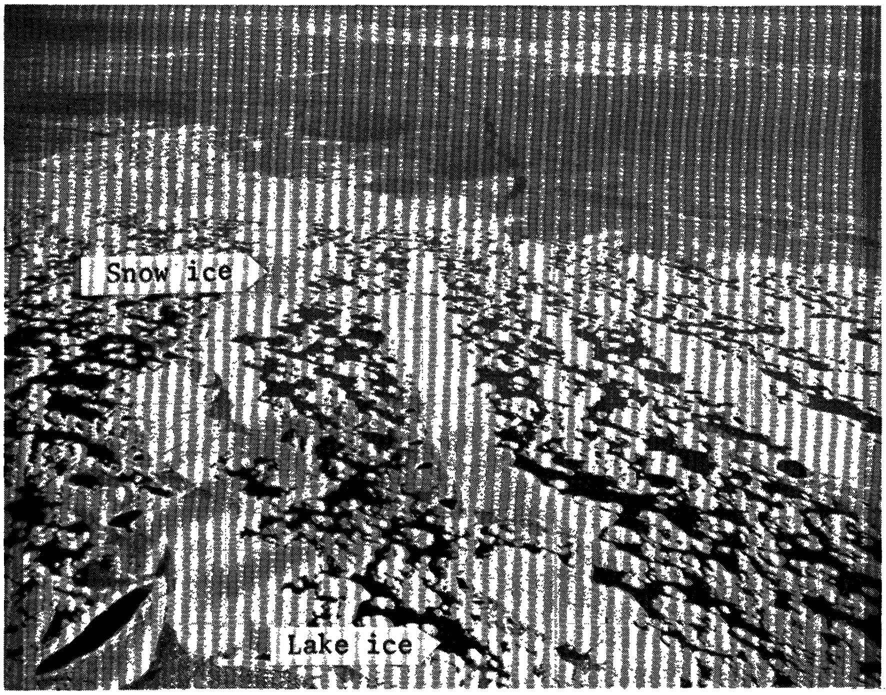

FIG. 9. EFFECTS OF SNOW ON A WIND-TORN FRAZIL ICE SKIM. The long irregular white zones are former areas of open water between frazil ice floes (similar to Fig. 8) which were blanketed by snow now frozen to snow ice. The small irregular white spots are breaks in the frazil ice skim which have been filled with snow. The black areas are frazil ice skim which has thickened to form an ice skin. Lake Huron (southwestern portion), 2/5/65. Altitude: 1800 ft.

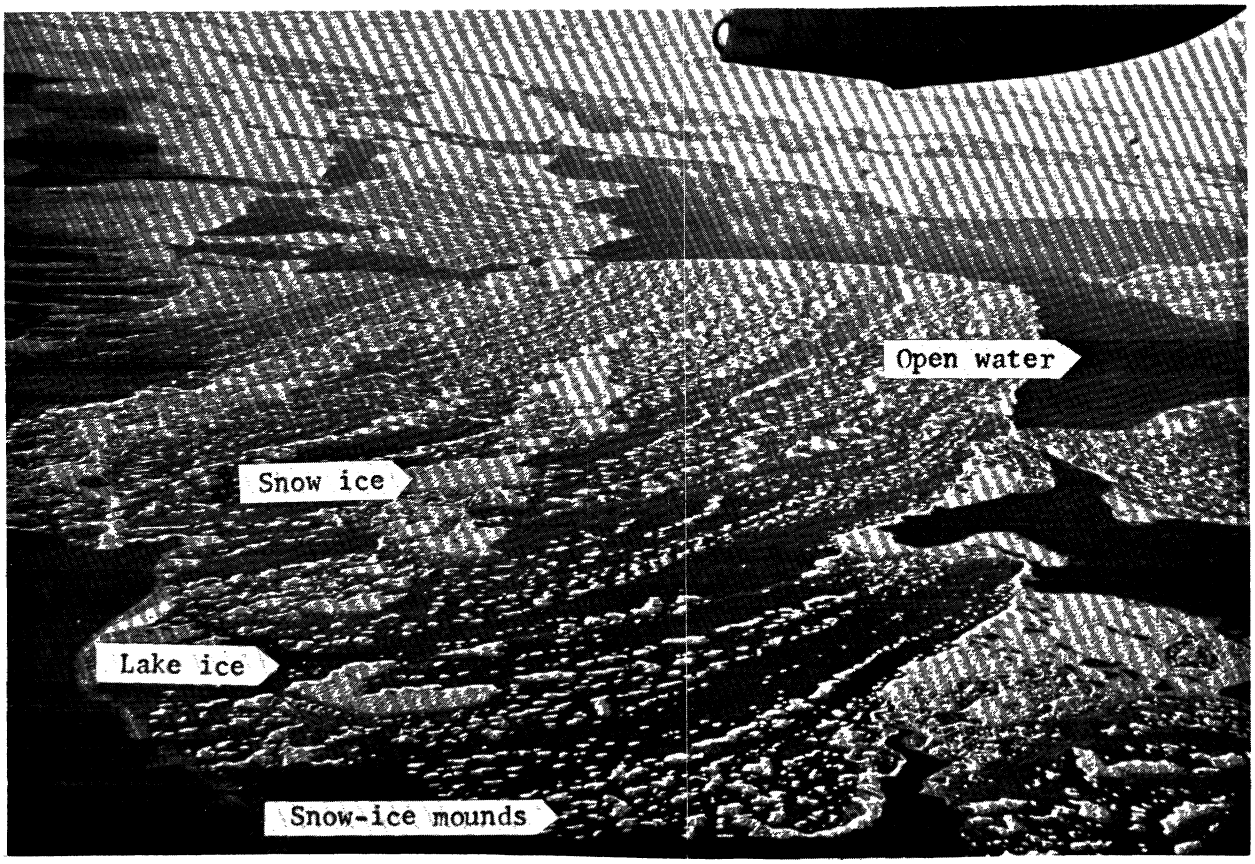

FIG. 10. EFFECTS OF BLOWING SNOW ON A FRAZIL ICE SKIM. Flexures caused by wave action made linear openings in the ice sheet. Wind-blown snows filled these breaks to produce the above pattern. The original ice skim has thickened to form floes of new ice. Lake Huron (southwestern portion), 2/5/65. Altitude: 1500 ft.

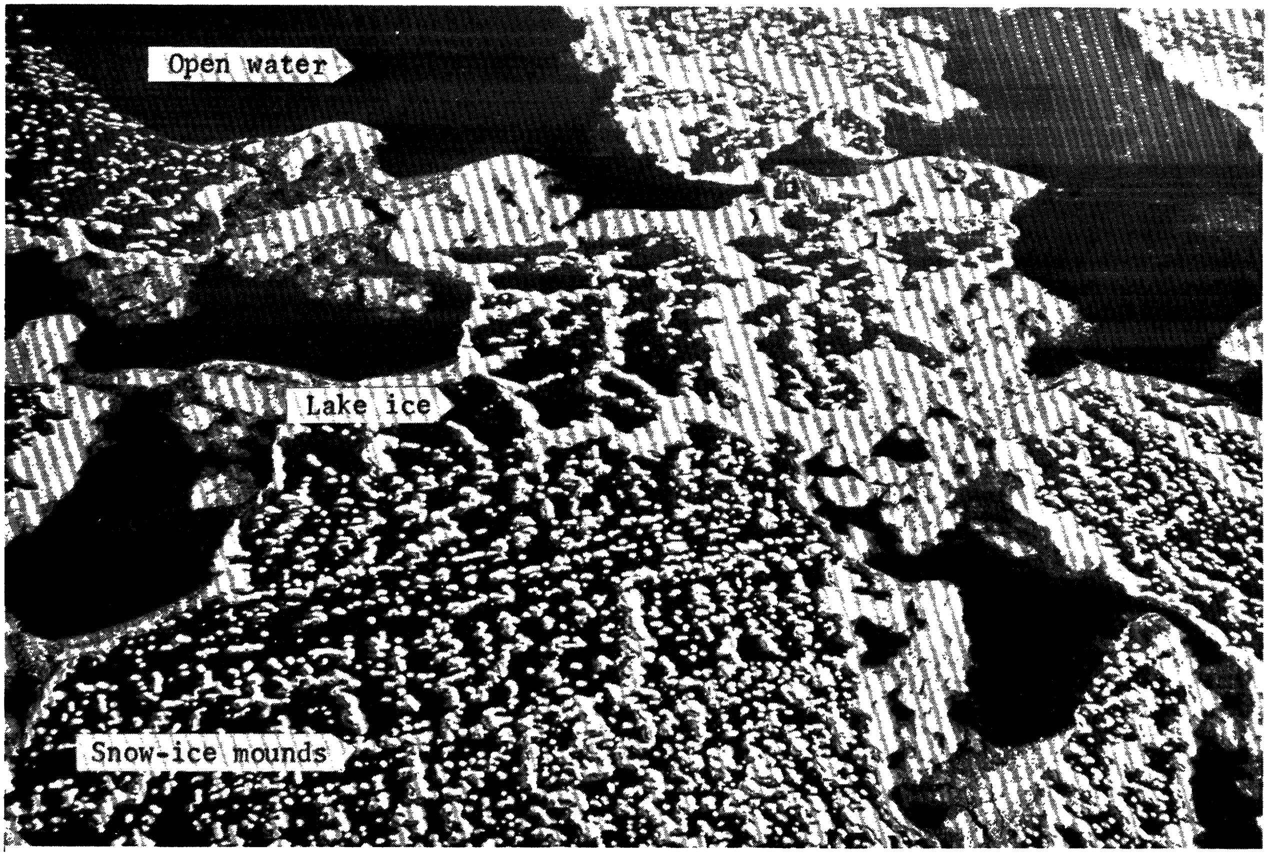

FIG. 11. DETAIL OF THE EFFECTS OF BLOWING SNOW ON A FRAZIL ICE SKIM. Blowing snow has accumulated in the breaks in the ice skim to begin the formation of snow-ice mounds. The cores of these mounds may be slush protected from freezing by the accumulation of dry snow. Lake Huron (southwestern portion), 2/5/65. Altitude: 1500 ft.

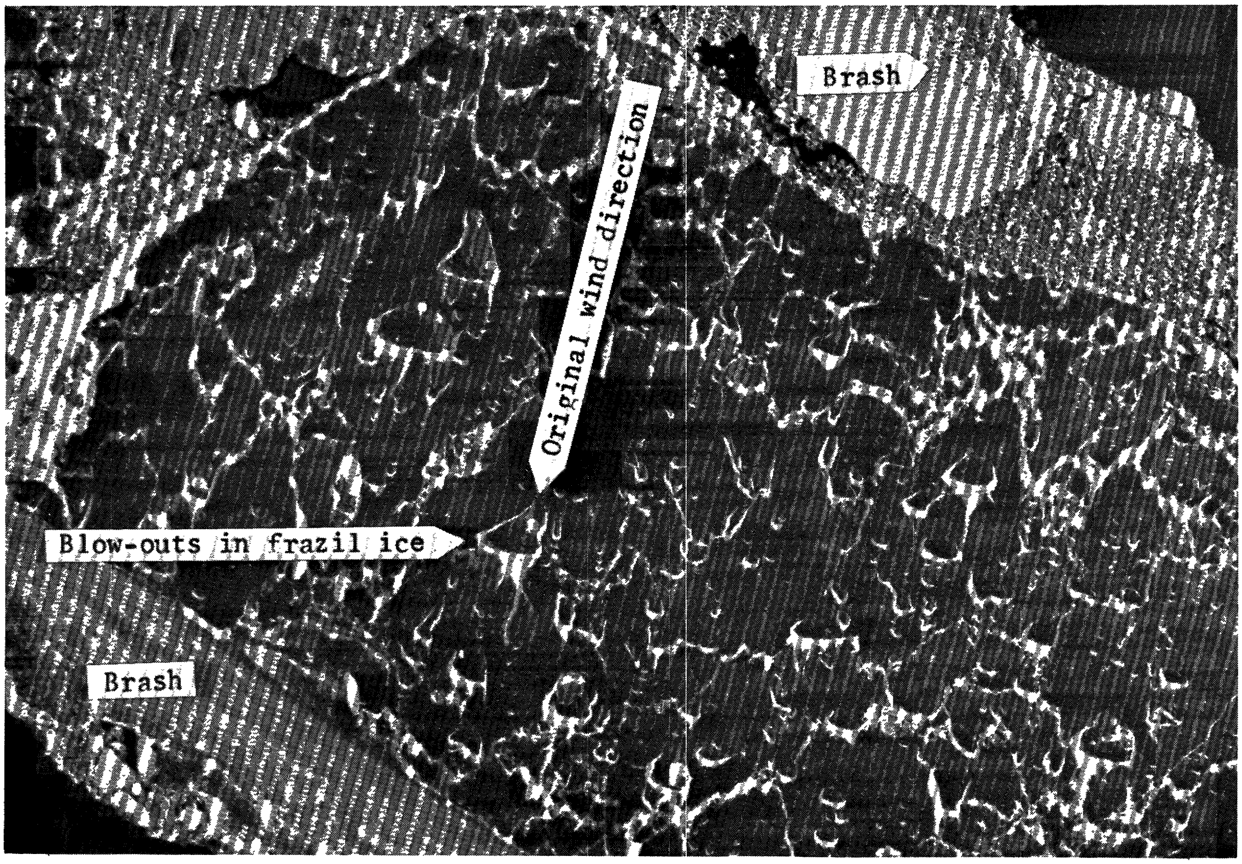

FIG. 12. RELICT PATTERNS OF INITIAL ICE FORMATION. This surface pattern is observed in a thick ice floe and is relict from a process of initial ice formation. The original wind direction can be inferred both from the shape of the original break in the ice skim and from the white rim of wind blown frazil ice. Lake Erie, Photo 9L-62-1R.

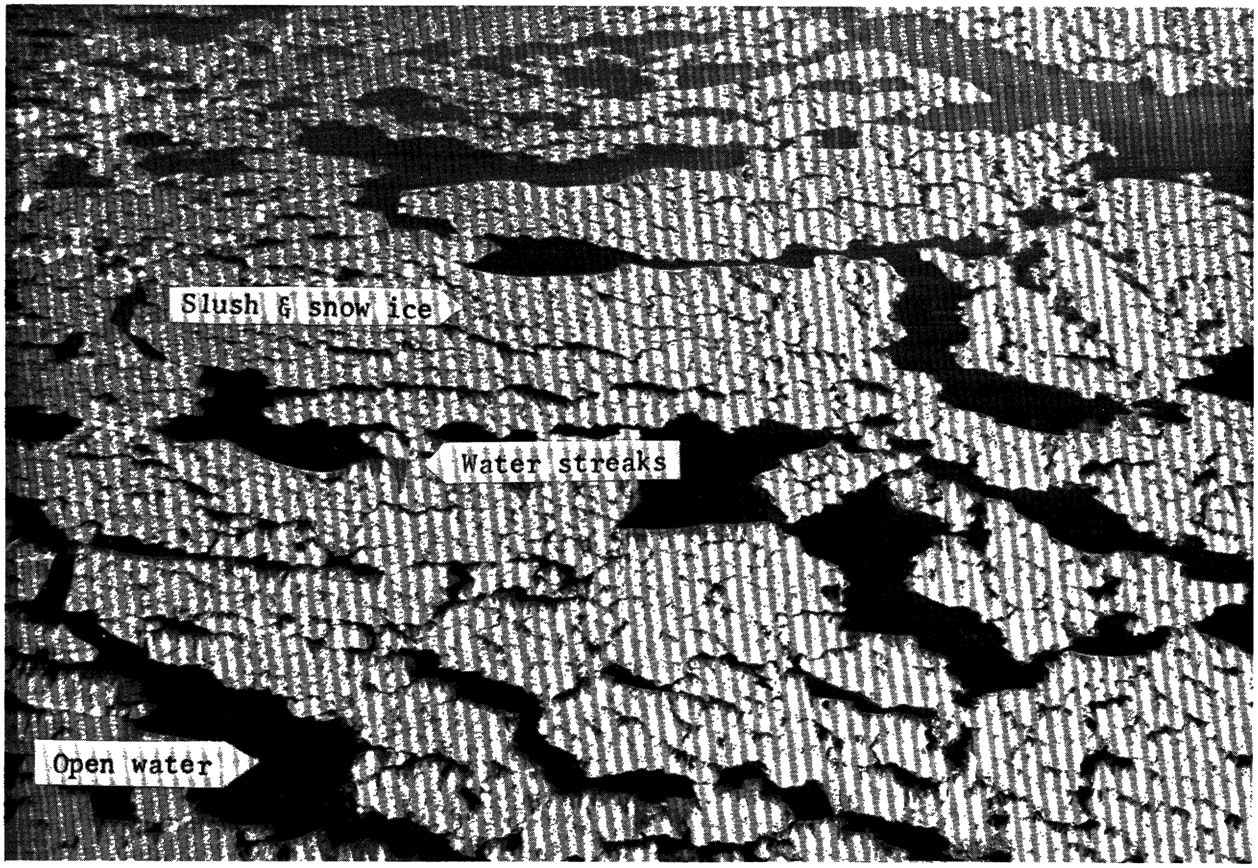

FIG. 13. THICK SLUSH LAYER SHEARED BY WIND ACTION. A thick slush layer floating on the water surface has been sheared by wind action to produce this curded pattern. Lake Huron, 2/5/65. Altitude: 1800 ft.

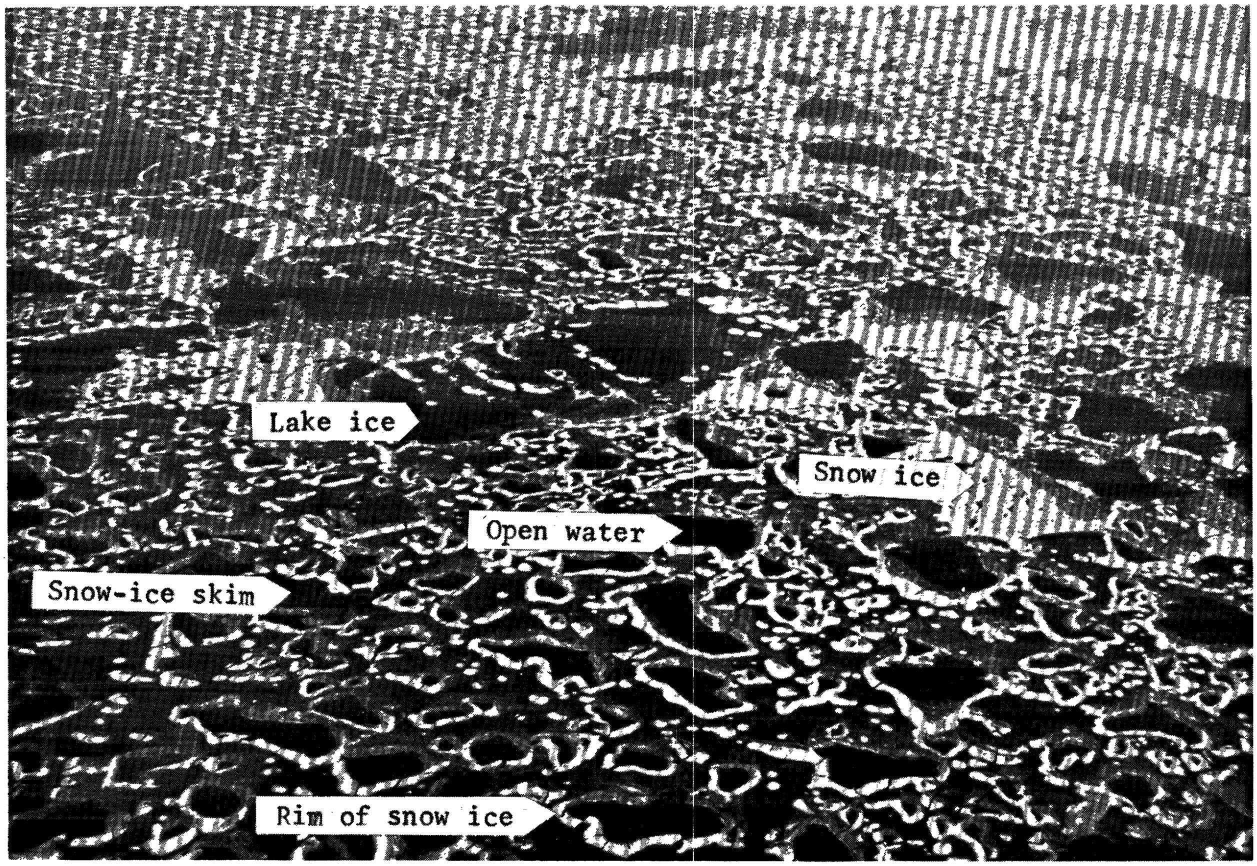

FIG. 14. WIND EFFECTS ON A THIN SLUSH LAYER. Wind friction has opened up areas of open water in the slush cover. This slush piled up on the leeward side forming white rims. The cracks in these rims indicate the slush has frozen to snow ice and was later cracked by the stresses set up by swells. Lake Huron, 2/5/65. Altitude: 1800 ft.

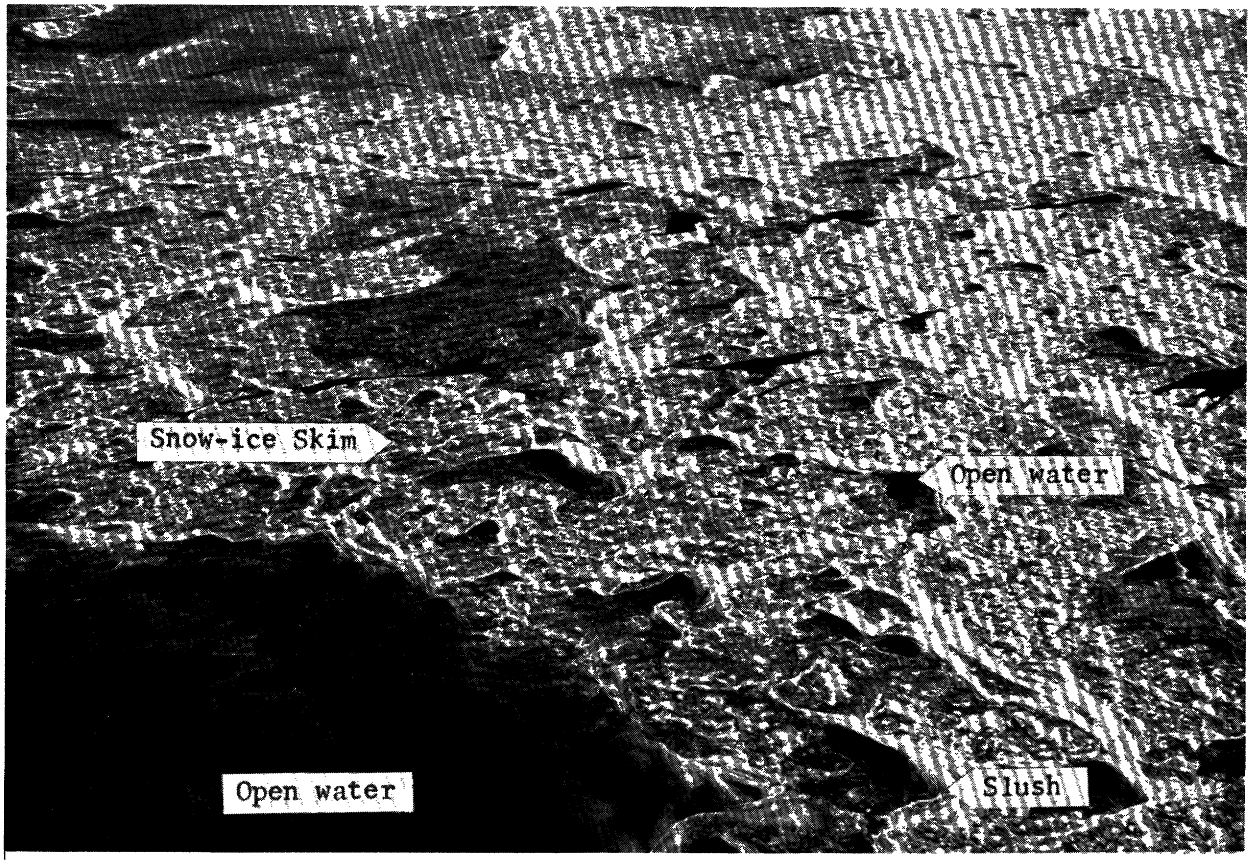

FIG. 15. PATTERNS IN THE SLUSH LAYER. Slush patterns observed in the initial ice skim often show several stages of formation. Two stages are indicated in the above illustration. The first slush layer has been worked by the wind and resulted in the curded pattern and open water areas. This slush layer froze and was followed by new snows which blew across the new ice into the areas of open water. Lake Erie, 2/4/65. Altitude: 800 ft.

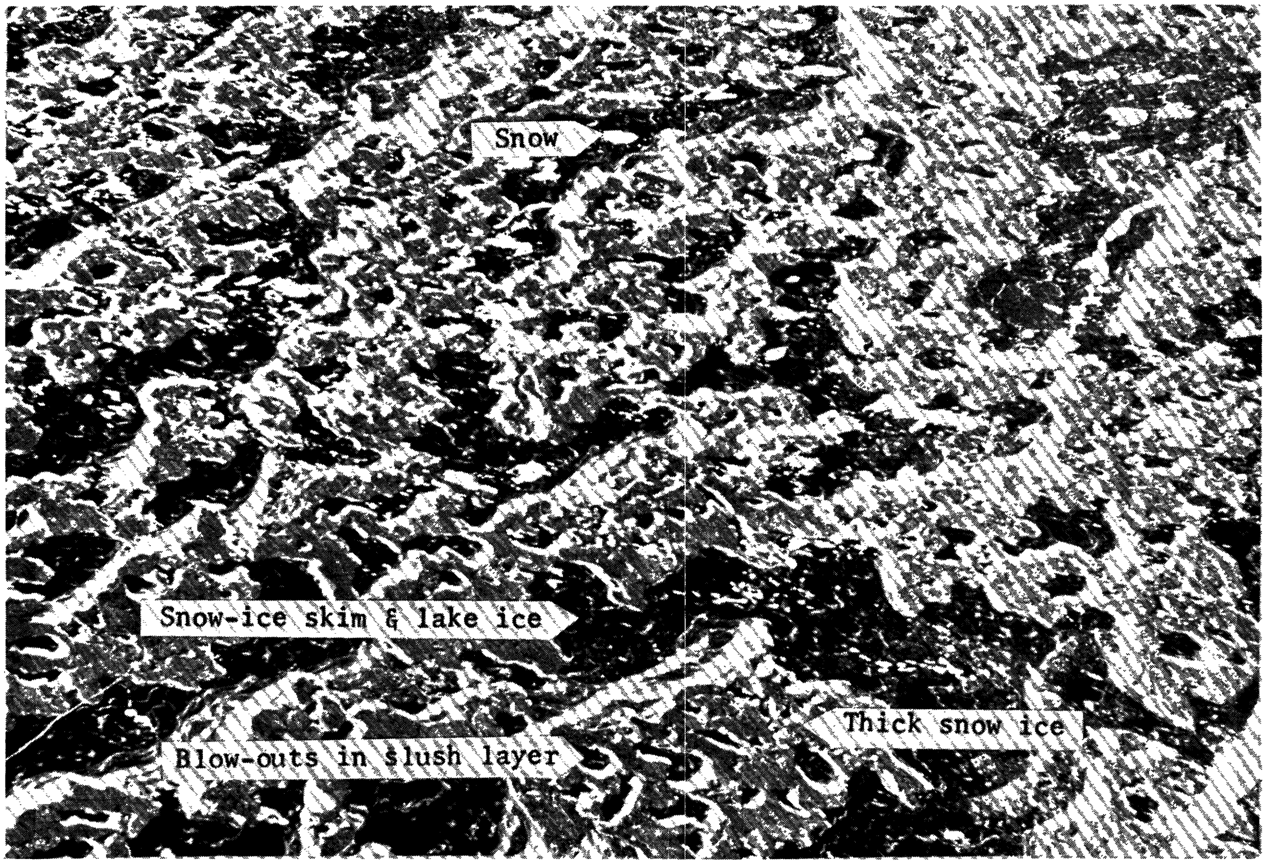

FIG. 16. RELICT SLUSH PATTERNS. Slush patterns similar to those in Figure 15 are seen here in a thick ice floe. Two stages of formation are seen in this ice sheet. In the first, a thick layer of slush was broken up by wind action with small areas of open water appearing within the larger slush floes. In the second stage, the areas of open water between floes were covered by a thin layer of wind-blown snow which drifted into festoons. Finally this whole mass froze into an ice sheet. Lake Erie, 2/4/65. Altitude: 800 ft.

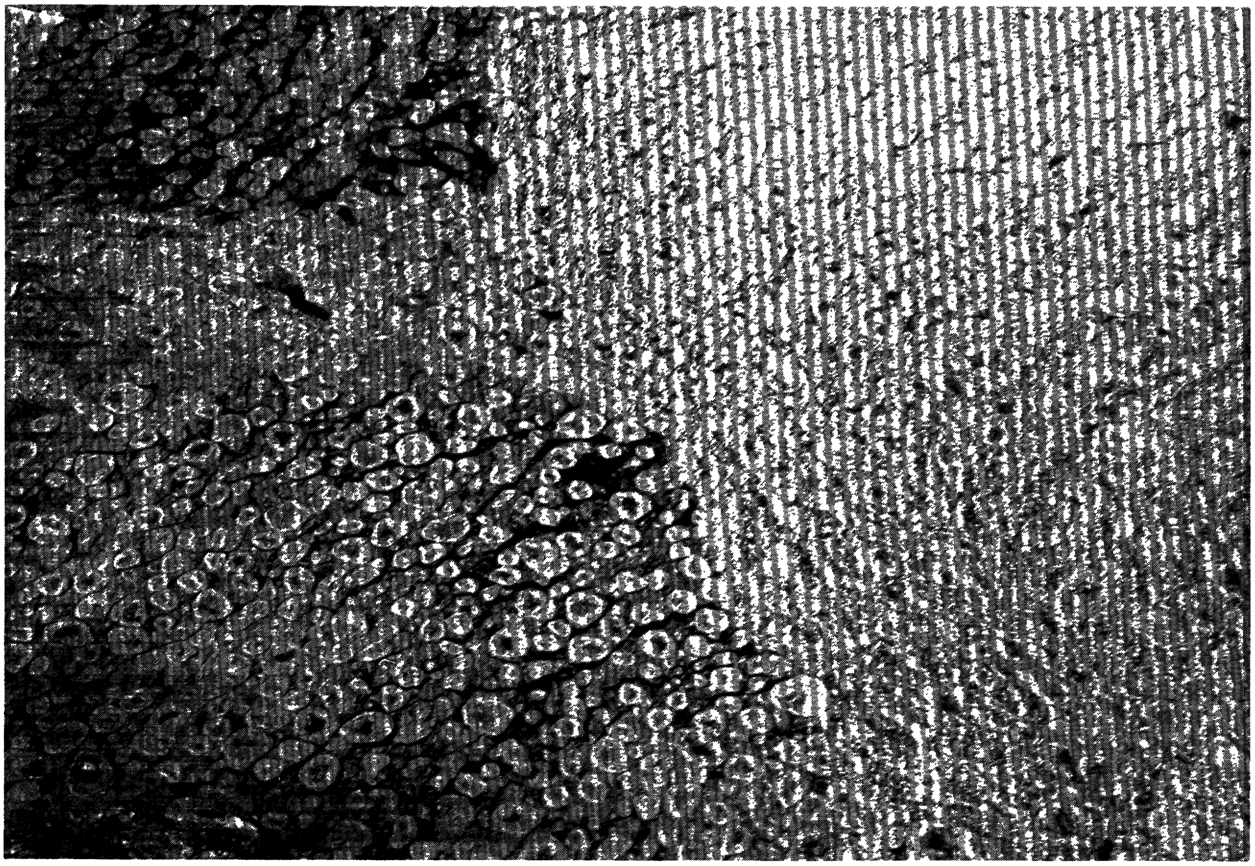

FIG. 17. PANCAKES OF SLUDGE. The pancakes are composed of small pieces of ice mixed with slush and were characteristic of the ice found in the eastern end of Lake Erie in the vicinity of Buffalo, N. Y., 2/4/65. Altitude: 800 ft.

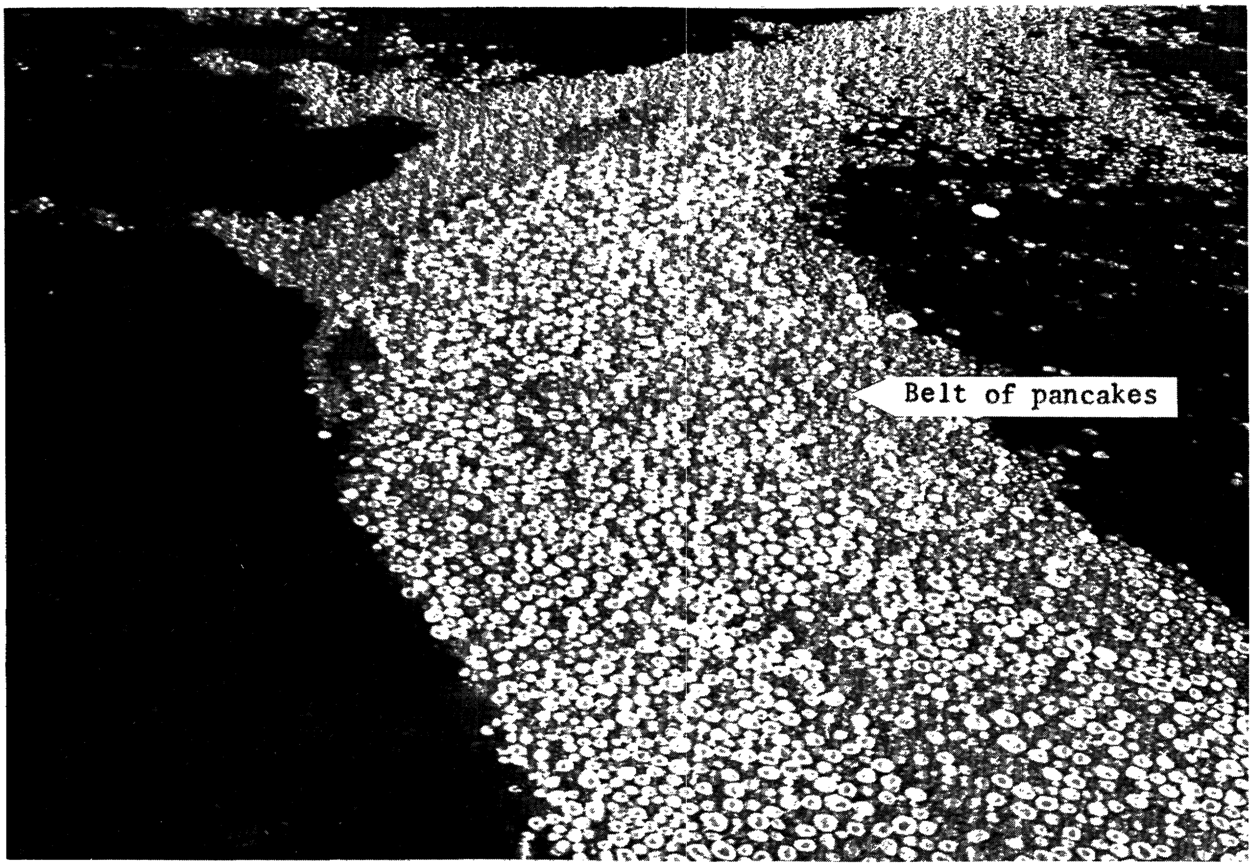

FIG. 18. PANCAKES OF NEWLY FORMED ICE. The raised rims and circular appearance are the result of constant rotation and collision of the cakes against one another caused by water turbulence. Lake Michigan, 1/28/65. Altitude: 800 ft.

BALL ICE FORMATION

Ball ice consists of roughly spherical masses of slush and frazil ice which accrete in turbulent water.

Loewe (1949) reported ball ice 3-5 cm in diameter in the sub-Antarctic waters of the South Atlantic and ascribed its origin to the accretion of slush and frazil ice.

Ball ice in the Great Lakes was observed by the writer in a nearshore zone of Lake Huron in the Rogers City area, Michigan. The ball ice formation was observed during a time of intense, local snow squalls which left patches of slush on the water surface. This ball ice was composed principally of slush which was shaped by the turbulent water conditions offshore from the cliffed icefoot into lumps and balls up to 1 meter in diameter (see Fig. 19). The lumps that formed in the less turbulent zones, a few tens of meters offshore, were flattened discs, while those that entered the extremely turbulent zone near the ice foot accreted into spheres.

Water turbulence at the foot of the icefoot stirred sand into suspension causing lumps entering this zone to accrete concentric bands of sand and slush (see Fig. 20). As a result of intense wave action these balls were thrown onto the icefoot where they froze and added sand and ice to the barrier. In other cases the ball ice was carried by winds and currents into coves where it collected to form a uniquely structured ice sheet (see Fig. 21). This drift of the ball ice serves to redeposit sand both along the shore and in deep-water sites.

Ball ice has been observed in other areas of the Great Lakes. During ice reconnaissance flights over Lake Superior in early January, the writer observed wide zones of this type of ice along the shoreline west of the Keweenaw Peninsula and along the Marquette shoreline. In these areas rough lumps up to 2 meters in diameter were frequently observed. Extensive fields of loose ball ice were observed in the western basin of Lake Erie, while later in the season similar fields were observed frozen in a matrix of clear ice (Fig. 22). Ball ice has also been frequently observed along the Lake Ontario shoreline east of Oswego, N. Y. (A. G. Ballert,* Personal communication).

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*Director of Research, Great Lakes Commission, Ann Arbor, Mich., 1965.

An extensive area of ball ice formation was observed in the western end of Lake Ontario in the vicinity of Port Weller. In this area a zone 3-5 km in width was composed of long, irregular belts of ball ice parallel to the shoreline. In a wide zone along the shore the ball ice was heavily concentrated by the winds (Fig. 23). At the outer edge, the ball ice formed streaks aligned with the wind and consisted of roughly parallel belts a few tens to a hundred meters apart. Ball ice diameters were approximately 30-76 cm (Figs. 24, 25).

The pattern of distribution of the ball ice belts suggests that two processes were at work. The outer belts aligned with the wind were the result of pure wind streaks. This type of streak represents the convergence zones in a roll-type cellular motion in the surface water layer (Langmuir 1938; Woodcock 1944).

In the inner zone the belts of ball ice were aligned parallel with the shoreline, which suggests the influence of internal waves at the boundary between the lighter, colder waters of the upper zone and the heavier, warmer water beneath. A similar phenomenon of water slicks running parallel to the shore and generated by internal waves has been observed along the California coast by Dietz and Lafond (1950).

It is evident that ball ice is a feature common to all of the Great Lakes and can occur at any time during the winter where water turbulence breaks up a slush layer. Fields of ball ice can freeze into ice sheets conglomeratic in structure, and where formed in turbulent nearshore zones serve to redistribute sand to sites along the shore and in deeper water.

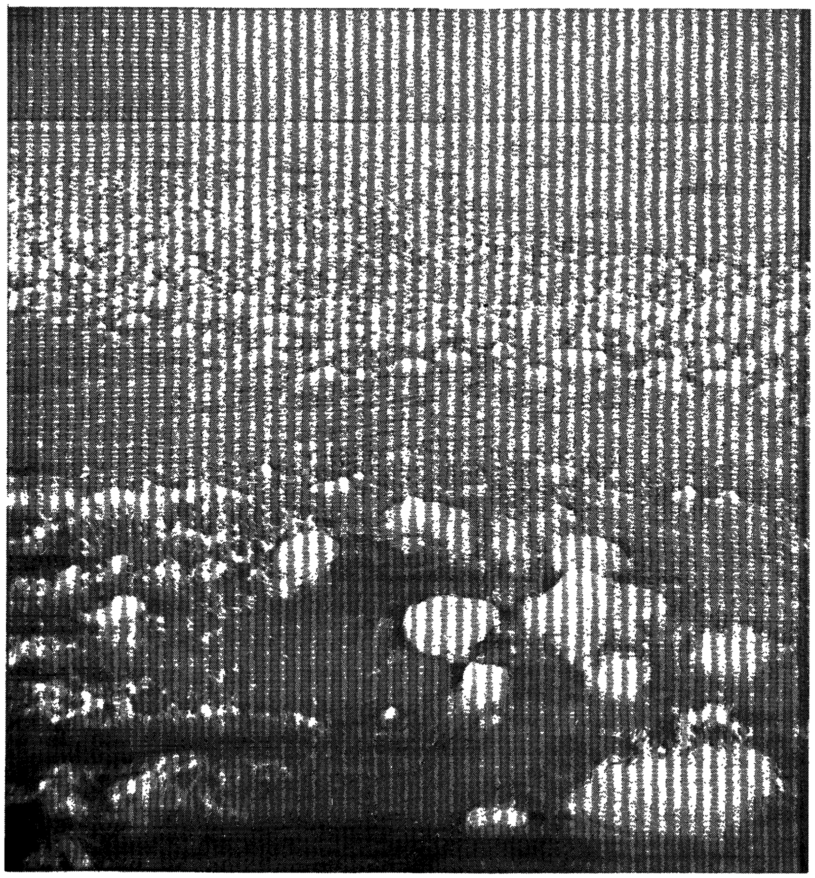

FIG. 19. BALL ICE FORMATION IN A NEARSHORE ZONE. Water turbulence in a nearshore zone produced ball ice from the accretion of slush and frazil ice. The lumps were roughly shaped offshore and later came to spherical form in the extreme water turbulence in front of the icefoot cliff. Lake Huron (Rogers City, Mich.).

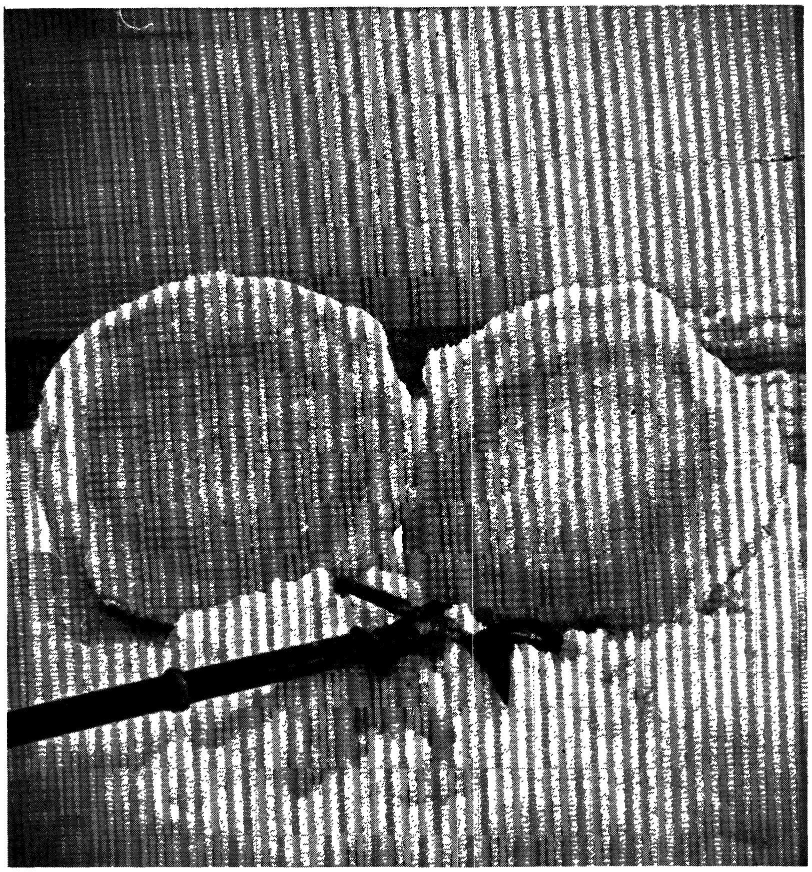

FIG. 20. CROSS SECTION OF BALL ICE. The diameter of ball ice formed in the nearshore ranged from a few centimeters to approximately 1 meter. In the zone immediately offshore from the icefoot cliff, water turbulence caused sand to be thrown into suspension. Ball ice carried into this zone accreted a sand-slush layer each time it entered it. Lake Huron (Rogers City, Mich.)

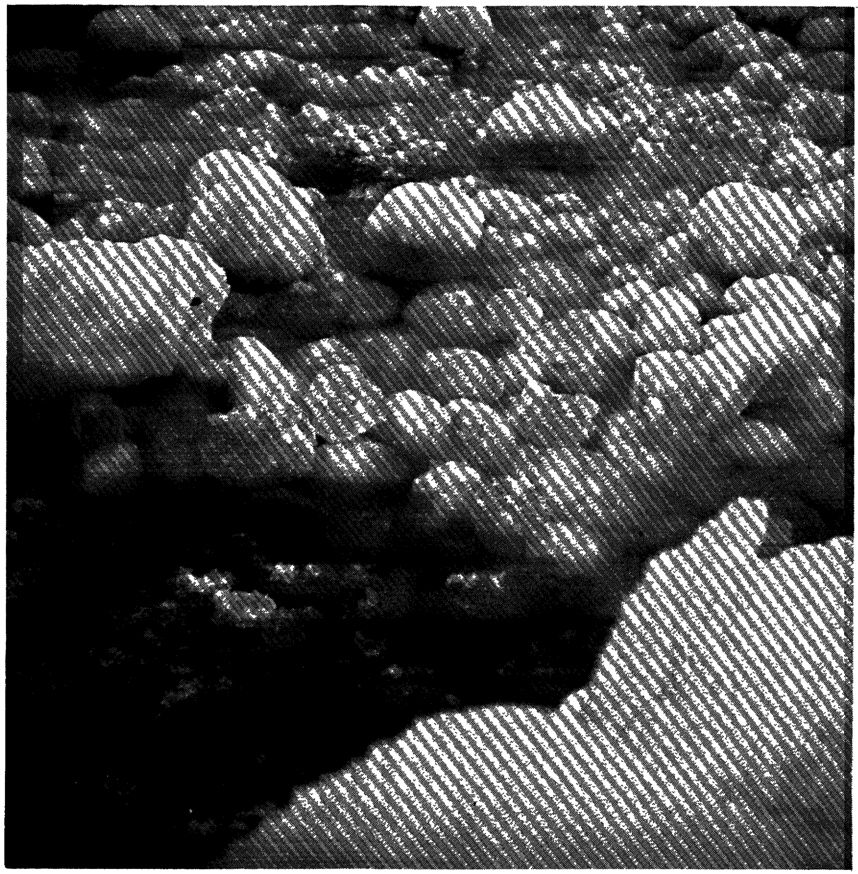

FIG. 21. CAKE OF BALL ICE. Ball ice in the nearshore zone was swept by winds into reentrants in the icefoot and accumulated to freeze into an ice sheet, conglomeratic in structure. Ball ice in the foreground is 15-40 cm in diameter. Lake Huron (Rogers City, Mich.).

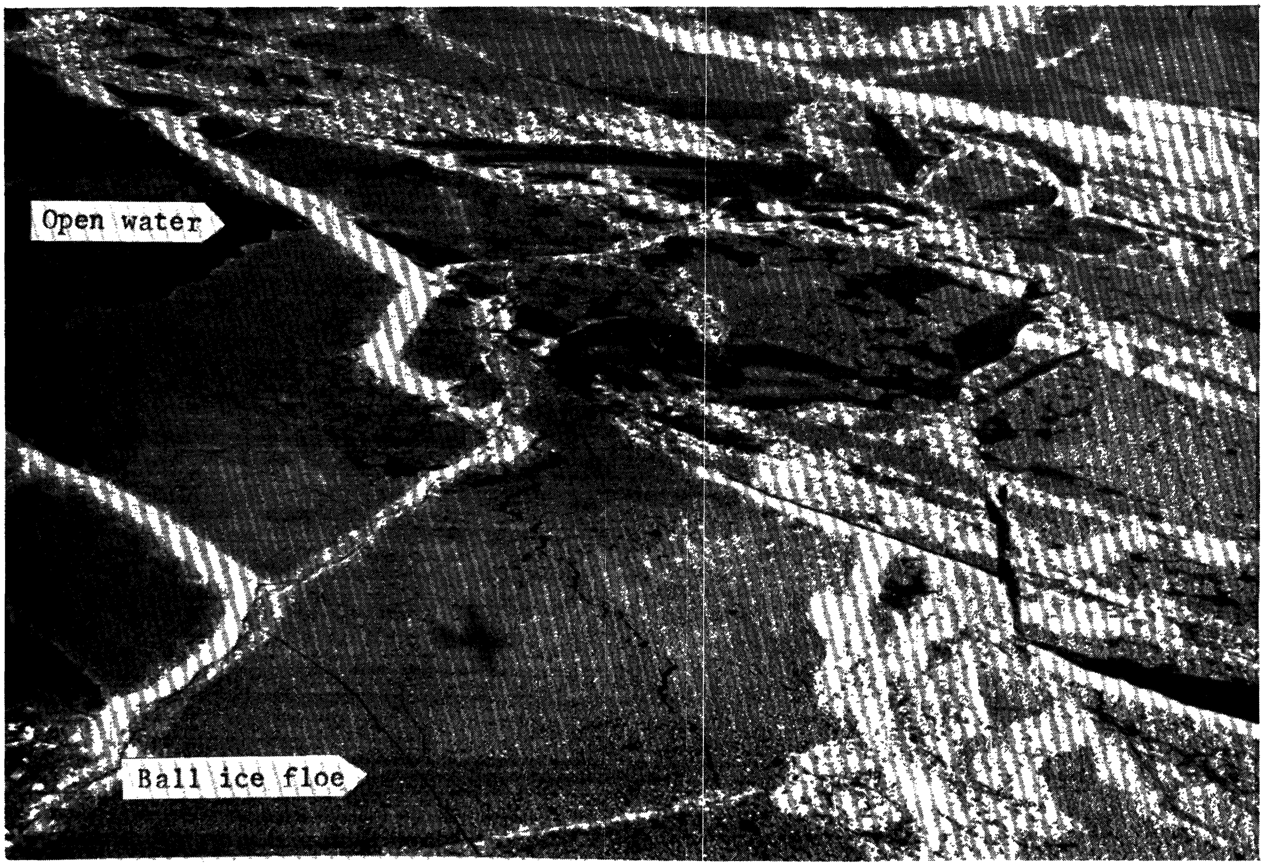

FIG. 22. FLOES OF BALL ICE. Ball ice was observed to form during periods of heavy snowfall in midlake locations in western Lake Erie. The ball ice was evenly distributed on the water surface and was frozen in a clear matrix of lake ice. Lake Erie, 2/4/65. Altitude: 800 ft.

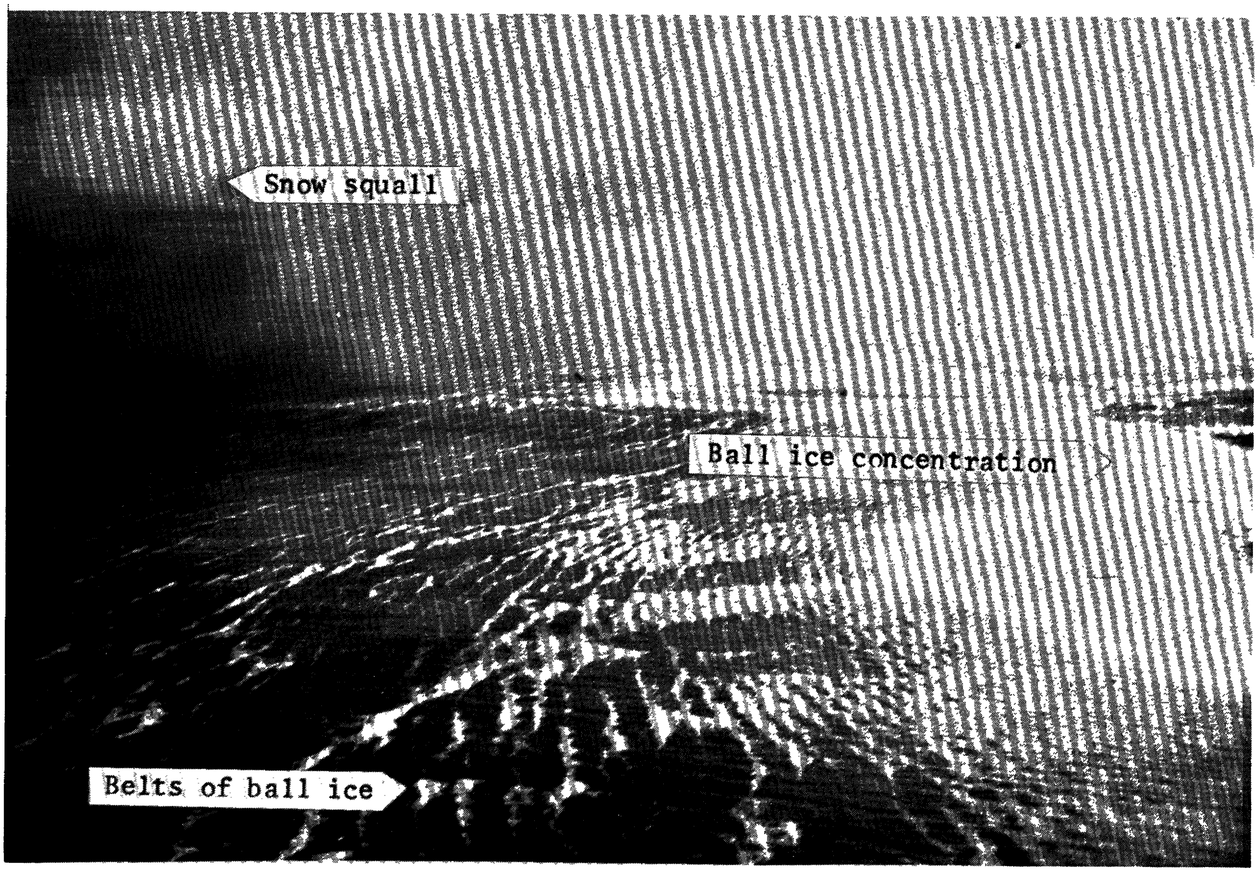

FIG. 23. BALL ICE FORMATION IN OFFSHORE ZONES. Ball ice formation was observed in a zone 3-5 kilometers in width along the Lake Ontario shoreline near Port Weller. The ball ice was arranged in long irregular streaks roughly parallel to the shoreline with a heavy concentration in a wide zone near the shore. Heavy snow squalls were occurring in the area at the time of observation. Lake Ontario, 2/4/65. Altitude: 3000 ft.

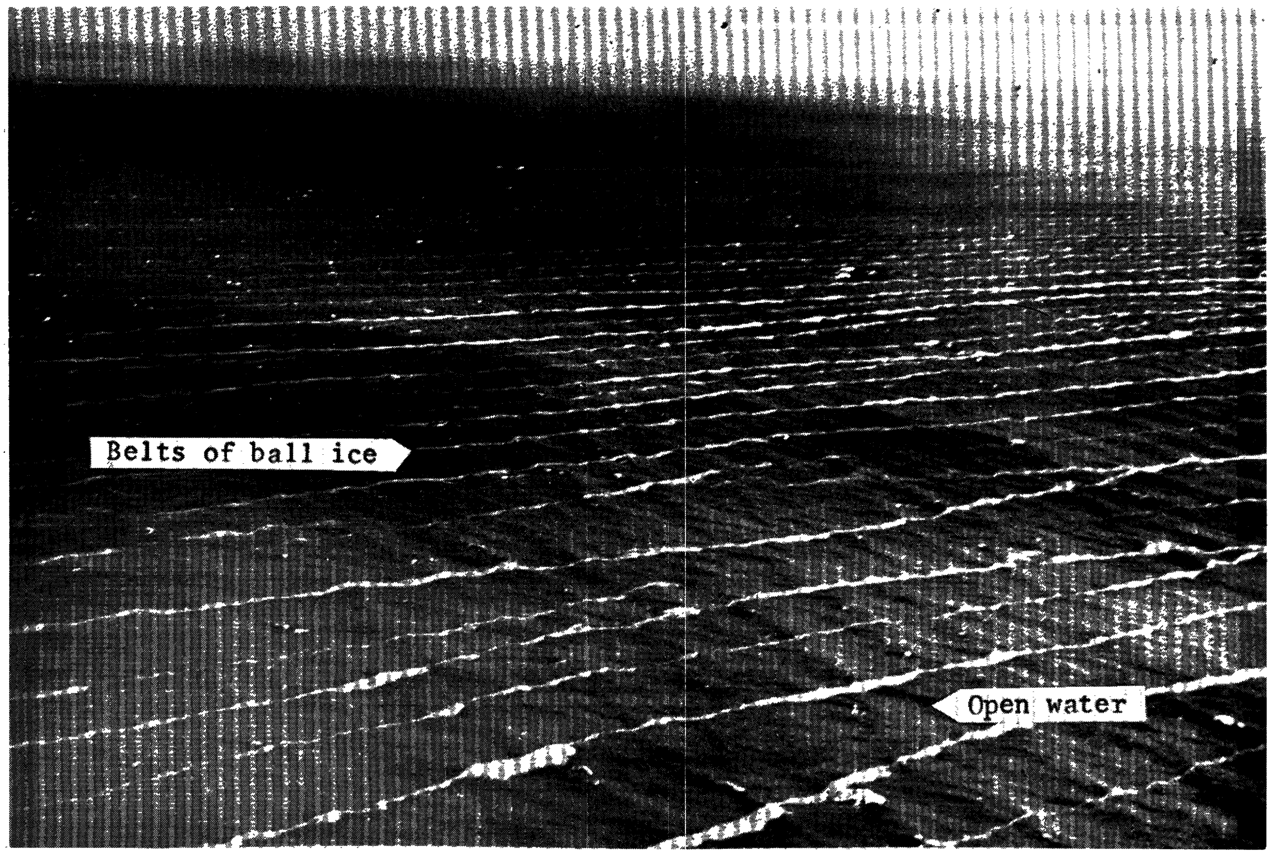

FIG. 24. BELTS OF BALL ICE. The ball ice formed in belts aligned with the wind and consisted of roughly parallel bands a few tens to one hundred meters apart. Lake Ontario, 2/4/65. Altitude: 500 ft.

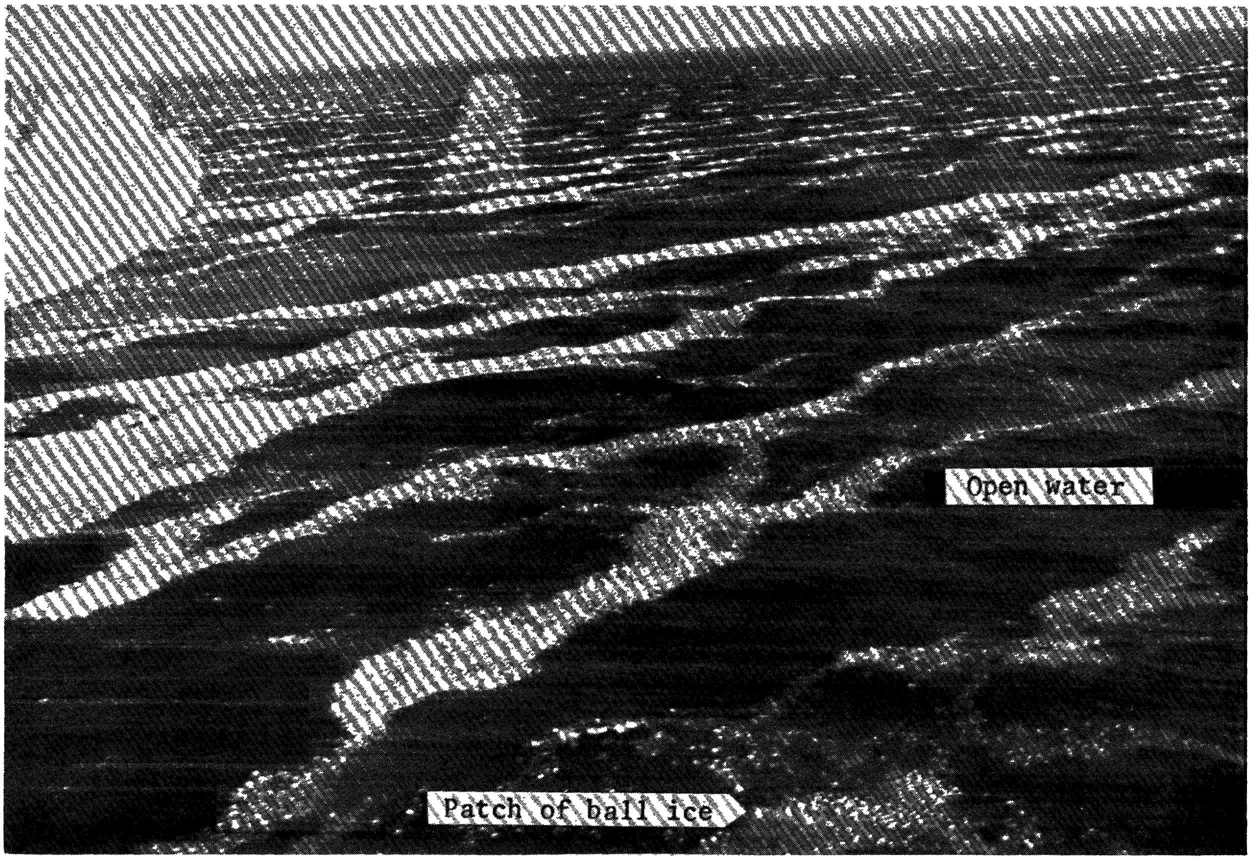

FIG. 25. DETAIL OF BALL ICE BELTS. The belts were arranged approximately parallel to the wind (18 knots). Ball ice diameters were estimated to range between 30-75 cm from comparisons with waterfowl. Lake Ontario, 2/4/65. Altitude: 200 ft.

ICEFOOT FORMATION

The icefoot is a striking feature along considerable stretches of Great Lakes shorelines. The mode of formation and the form are dependent on the shoreline environment and the weather which prevailed at the time of formation.

The types of icefoot which were originally described by Wright and Priestly (1922, p. 295-324) along the Antarctic coastlines may be found in modified form along the Great Lakes shorelines. These main types of icefoot include the storm, the drift, the pressure, the stranded floe and the "tidal" platform. The writer's aerial observations indicated that the storm icefoot was the most common type, which was in some cases modified by accumulations of drift snow. In the varied meteorological and shoreline conditions found in the Great Lakes, it is to be expected that these other types will be observed in the future.

Air and water temperatures must be sufficiently low before an icefoot begins to form. The conditions favorable for icefoot formation are broad open shorelines gradually sloping below water level, and facing so that wind-blown spray is carried inland toward the shore to freeze. The character of growth of an icefoot differs during different periods of the winter. During the course of the winter the icefoot may suffer periods of denudation alternating with periods of accretion. The development of an icefoot can be held at one stage by the early freezing of fast ice offshore.

An icefoot can be composed of any combination of frozen spray or lake water, snow accumulations, brash, stranded icefloes, and sand which is either thrown up on the icefoot by wave action or is blown out from the exposed beaches.

Observations of the icefoot along the shorelines of Lakes Superior and Erie indicated that the moderately steep portions of the shore were characterized by narrow terraces composed of frozen slush and brash thrown up by storm winds. The outer edge of this icefoot was often cusp-like in form, resulting from the mechanical and melting action of the waves. The inner portions of the cusps acted to concentrate the wave action, forming blowholes which threw spray back on the icefoot. An ice barrier composed of stranded ice floes and brash marked the location of offshore bars. The lagoon between the outer ice barrier and the icefoot proper was often covered by a sheet of brash. In some areas the shore portion of the icefoot was deeply mantled by drifting snow and in other cases lightly veneered with windblown sand.

It is possible that the lake equivalent of the tidal platform icefoot may form in extremely shallow shore zones of Lakes Erie and Ontario as a result of water-level differences caused by prevailing winds which expose these shallow areas to freezing temperatures.

Zumberge and Wilson (1954, p. 201-205) noted that the icefoot not only protected the shoreline from wave action for periods of three to four months but shifted the zone of wave scour to deeper water causing permanent effects.

In the spring, solar radiation causes candling of the ice as well as melting resulting from heat radiated from adjacent rock areas and from sand included within the icefoot. The icefoot is further denuded by the melting and mechanical action of the waves and the grinding action of ice floes. Drainage from the land and from thaw waters completes the dissection of the icefoot.

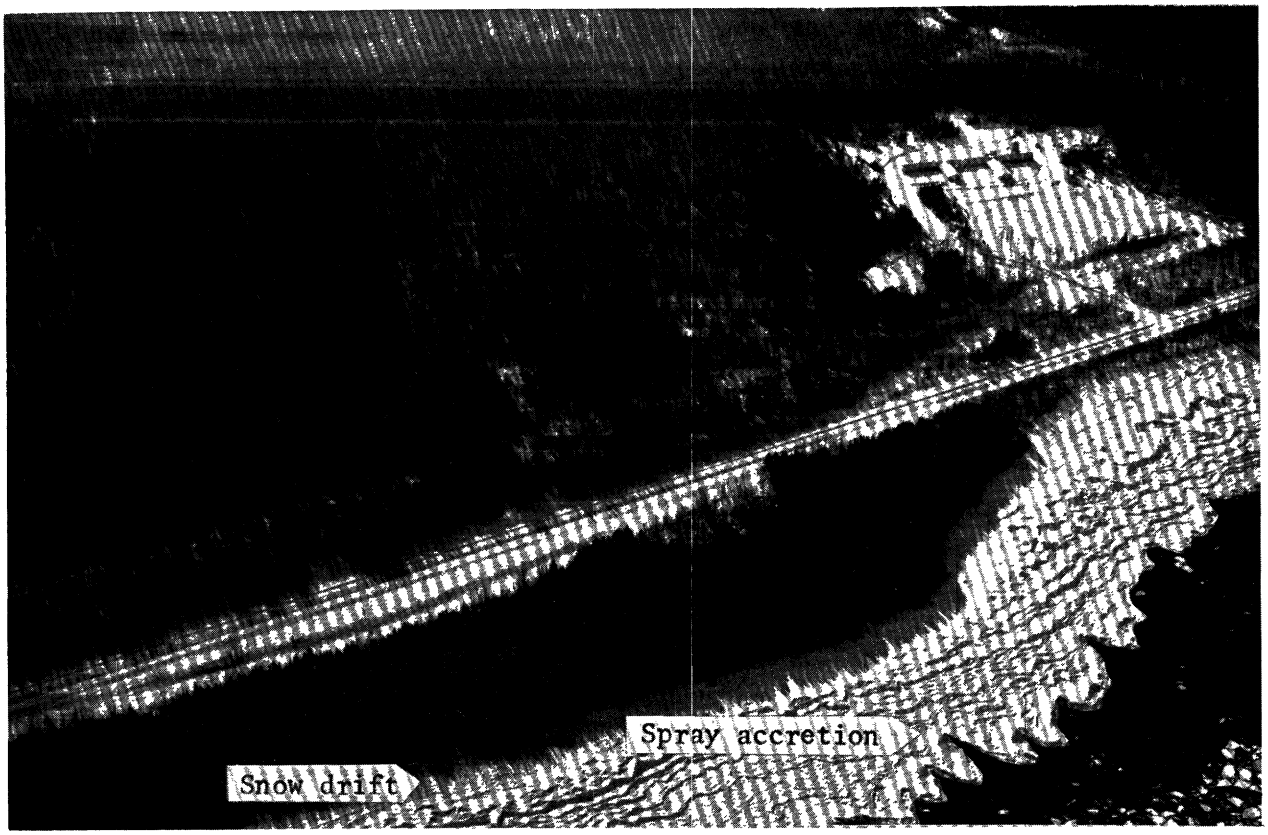

FIG. 26. STORM ICEFOOT ON A MODERATELY SLOPING SHORELINE. The narrow shore terraces are composed of frozen accumulations of wind-driven slush and brash on a moderately sloping shoreline. The cusp-like edge results from the solvent and mechanical action of waves. In a later period of formation the cusps have acted to concentrate the wave action so that spray has frozen and built up inland of these sharp reentrants. Drifting snow has begun to fill in the irregularities in the upper portion of the icefoot. Lake Superior (Grand Marais area, Mich.), 1/14/65.

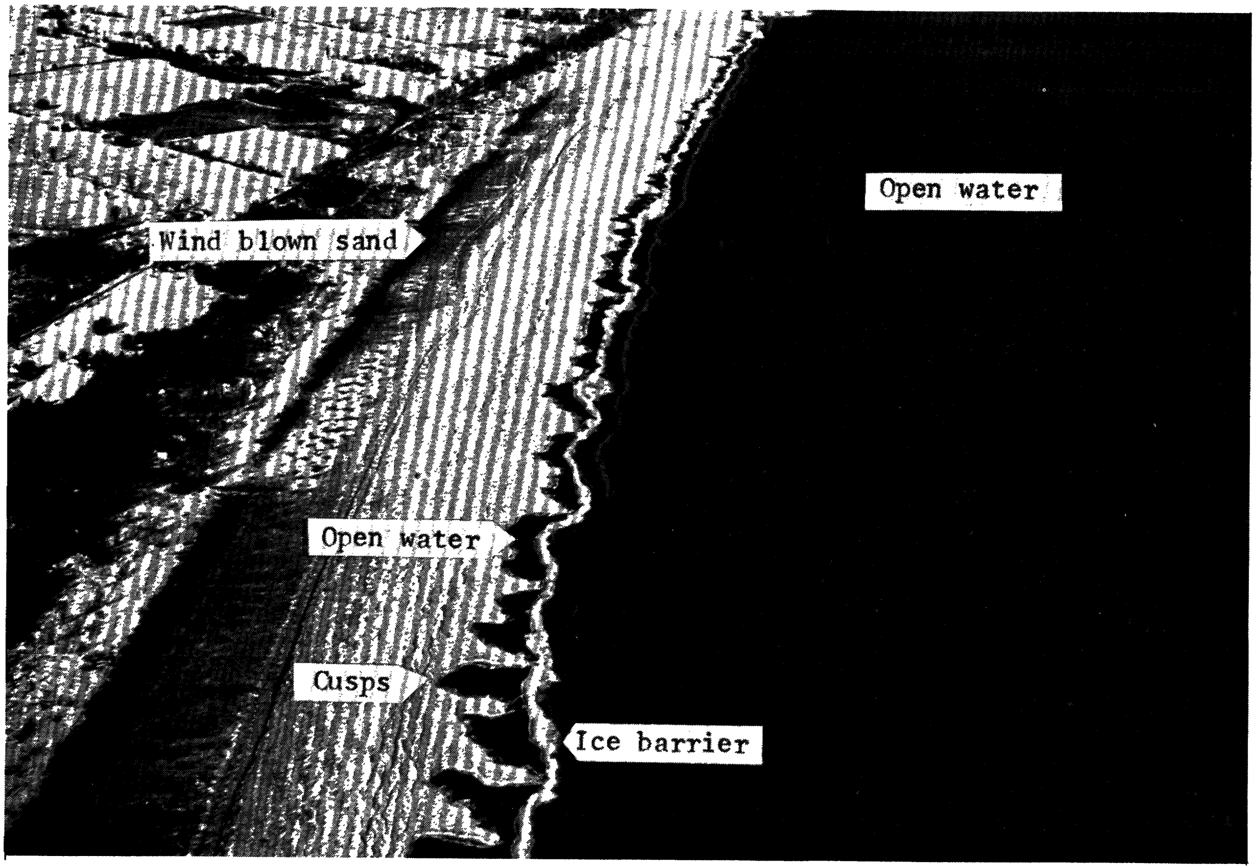

FIG. 27. STORM ICEFOOT WITH OFFSHORE BARRIER FORMED ON A GENTLY SLOPING SHORELINE. Accumulations of brash, slush and spray have gradually accumulated on this gently sloping shoreline. Periods of storm activity are marked by the long cliffed accumulations in the inner portion of the icefoot. The irregular cusped inner icefoot edge results from the denudation of wave action. The outer ice barrier has formed from grounded ice on an offshore sand bar. Wind-blown sand from the beaches mantles the inner edge of the icefoot. Lake Erie (shoreline west of Leamington, Ontario), 2/4/65.

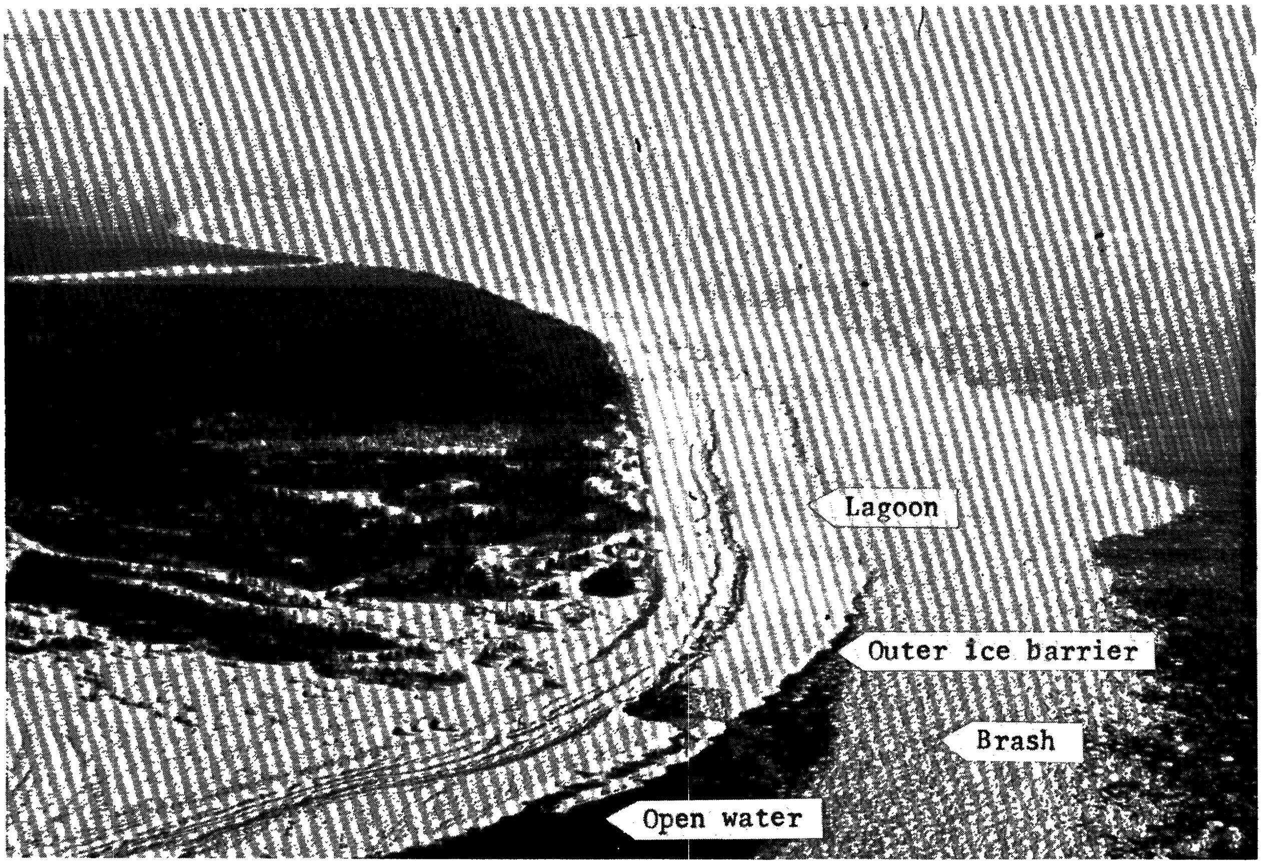

FIG. 28. STORM ICEFOOT WITH A LAGOON AND OFFSHORE BARRIER. The inner terraces reflect a series of storm accumulations on a shoreline where portions are moderately sloping. The lagoon between the inner and outer barrier is filled with frozen brash, possibly grounded. The outer ice barrier marks the position of an offshore bar, while loose brash drifts outside this barrier. Lake Superior (Whitefish Point, Mich.), 1/14/65.

FEATURES IN NEWLY FORMED ICE

There are surface features and patterns which appear in newly formed ice and which remain as the ice sheet thickens. The newly formed hard ice skin preserves the stirred and wrinkled patterns formed by surface currents during the formation of the frazil ice skim (Fig. 29).

Unique serrate and streaked patterns are produced when films of water are blown out over the ice sheet from leads and openings along fracture lines (Figs. 30-33).

Blowing snow collects at thaw holes in newly formed ice sheets and begins the formation of snow-ice mounds and ridges (Figs. 34-36). These thaw holes serve as wicks and allow lake waters to soak into the accumulating mounds of drifting snow.

Unique rectilinear thrust patterns were also observed to form when winds and pack ice pressures caused newly formed ice to form thrust structures. The patterns observed can be related in a general way to ice type and thickness (Figs. 37-42).

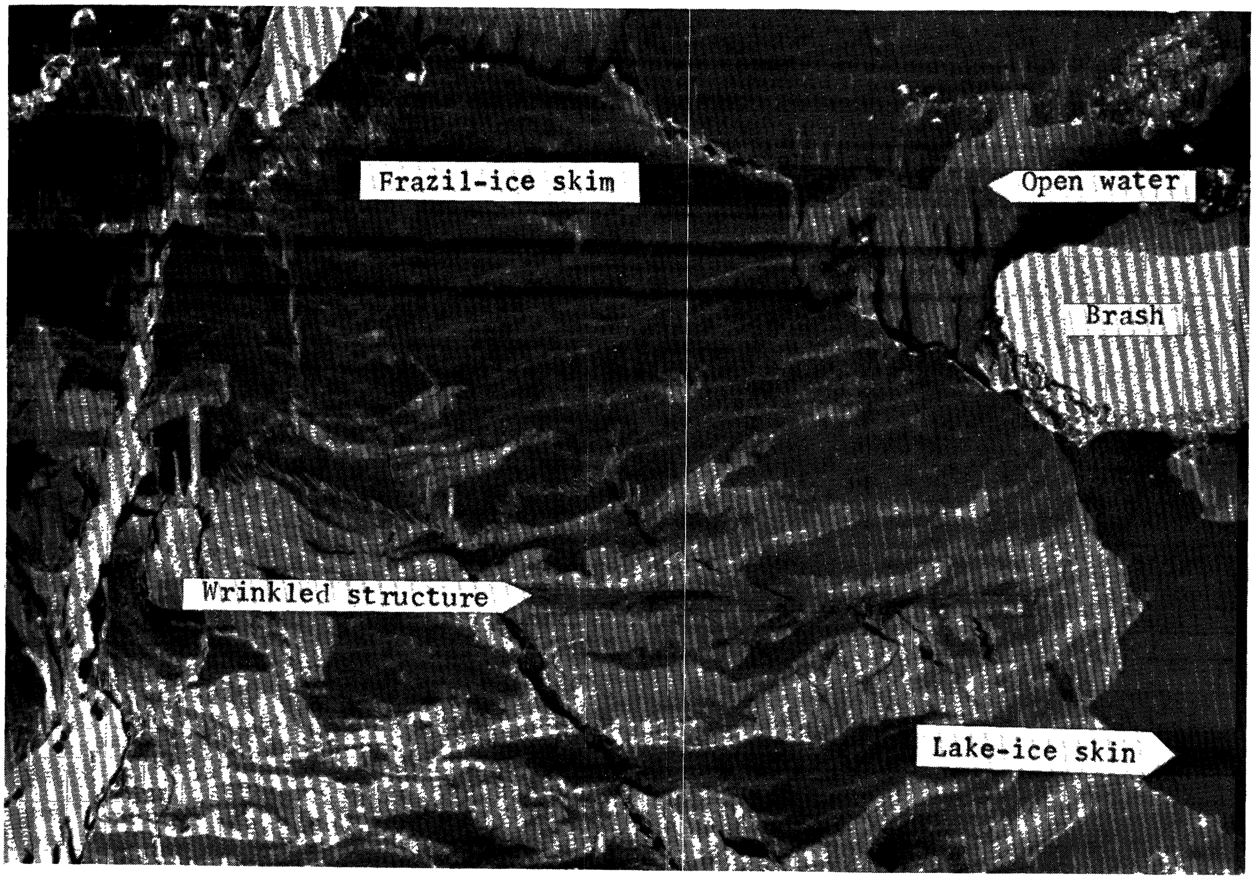

FIG. 29. WRINKLES IN THE FRAZIL ICE SKIM. This feature was formed by winds and currents when the ice skim was a mass of loose frazil ice crystals. At the stage pictured, the ice has frozen so that it shows features of overthrusting and fracturing. Lake Erie, Photo 9L-158-2R.

WATER STREAKS

Water streaks is the term used by the writer for the distinctive patterns formed when films of water are blown out over the ice sheet surface from leads and openings along fracture lines. These features have not been previously described in the ice literature.

These streaked water films have two basic patterns, one of which is sharply serrate at the ends and the other rounded and tongue-like. Variations on these patterns are caused by relative changes in wind direction either from true wind shifts or by rotation of the drifting ice sheet.

The streaked-out serrate patterns result when the water film remains unfrozen. On aerial photographs these patterns have been observed to extend several hundred meters downwind from the source of water (see Fig. 30).

Slight wind shifts while the water film is blowing out over the ice sheet cause the plumose structure seen in Figure 31. The gray albedo of this finely crystalline ice layer is in contrast to the darker albedo of the homogeneous and relatively coarsely crystalline sheet of lake ice.

It is suggested that the rounded tongue-like patterns result when the wind-blown water film becomes laden with frazil ice. The water-frazil ice mixture may blow out from the open water or the frazil ice may form within the water film as it blows across the ice sheet. The outer ends of the tongues in Figure 32 show a change in albedo which may result from the accumulation of frazil ice.

The effects of wind shifts during the streaking out of a frazil-laden water film can be observed in Figure 32. In this case each of the tongues follows the sudden shifts in wind direction. Figure 33 shows the irregular patterns which result in some cases.

While on flights over Lake Erie, the writer observed patterns of frozen and unfrozen water streaks which were in sharp contrast. The frozen water films displayed a brilliant, many-faceted reflection possibly produced by the film freezing with orientations similar to the underlying lake-ice crystals. Water films in the process of blowing out over the ice presented a homogeneous, darker appearance.

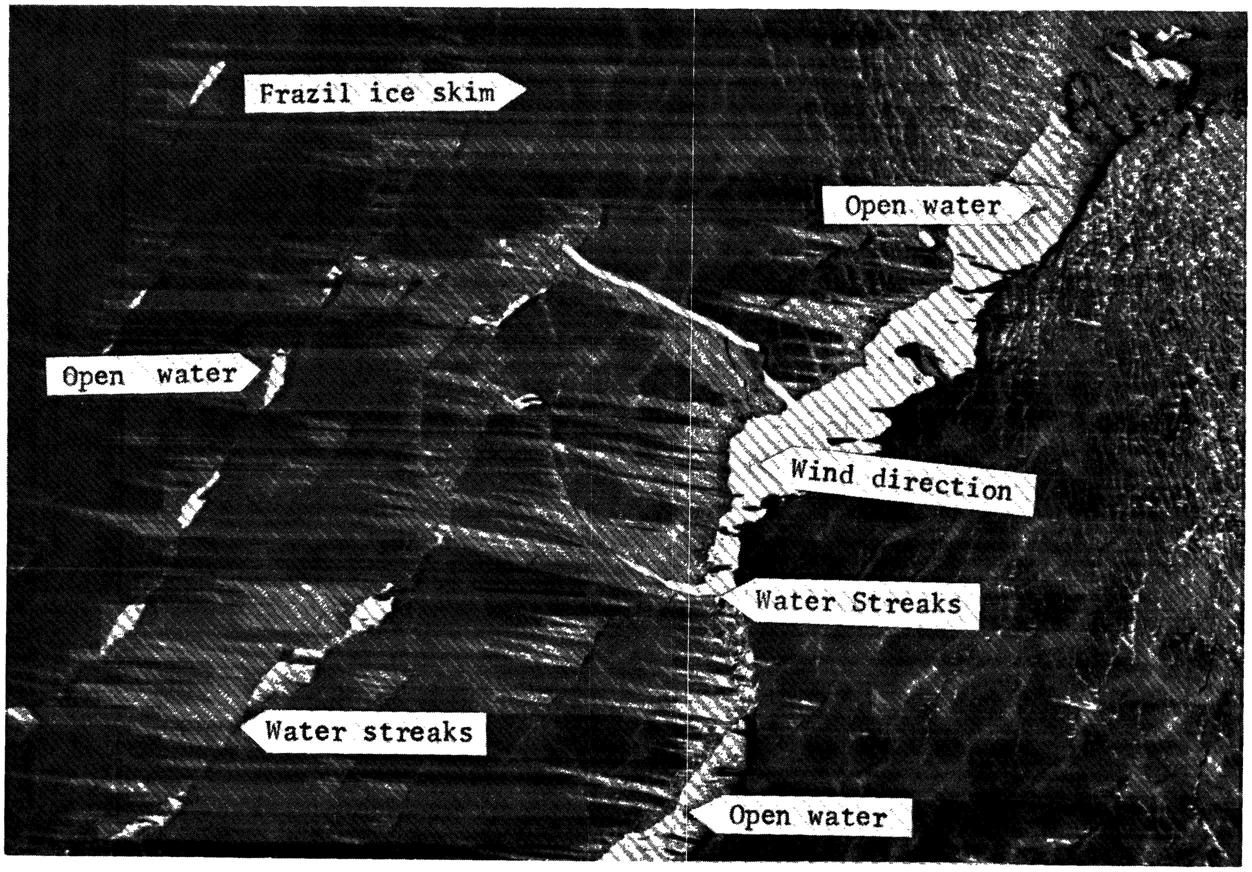

FIG. 30. WIND-BLOWN WATER STREAKS ON A FRAZIL ICE SKIM. An unusual feature is formed when a film of water is blown out onto the ice surface in long, plume-like extensions from cracks in the frazil ice skim. The streak in the center foreground extends approximately several hundred meters onto the ice surface. Lake Erie, Photo 9L-148-2R.

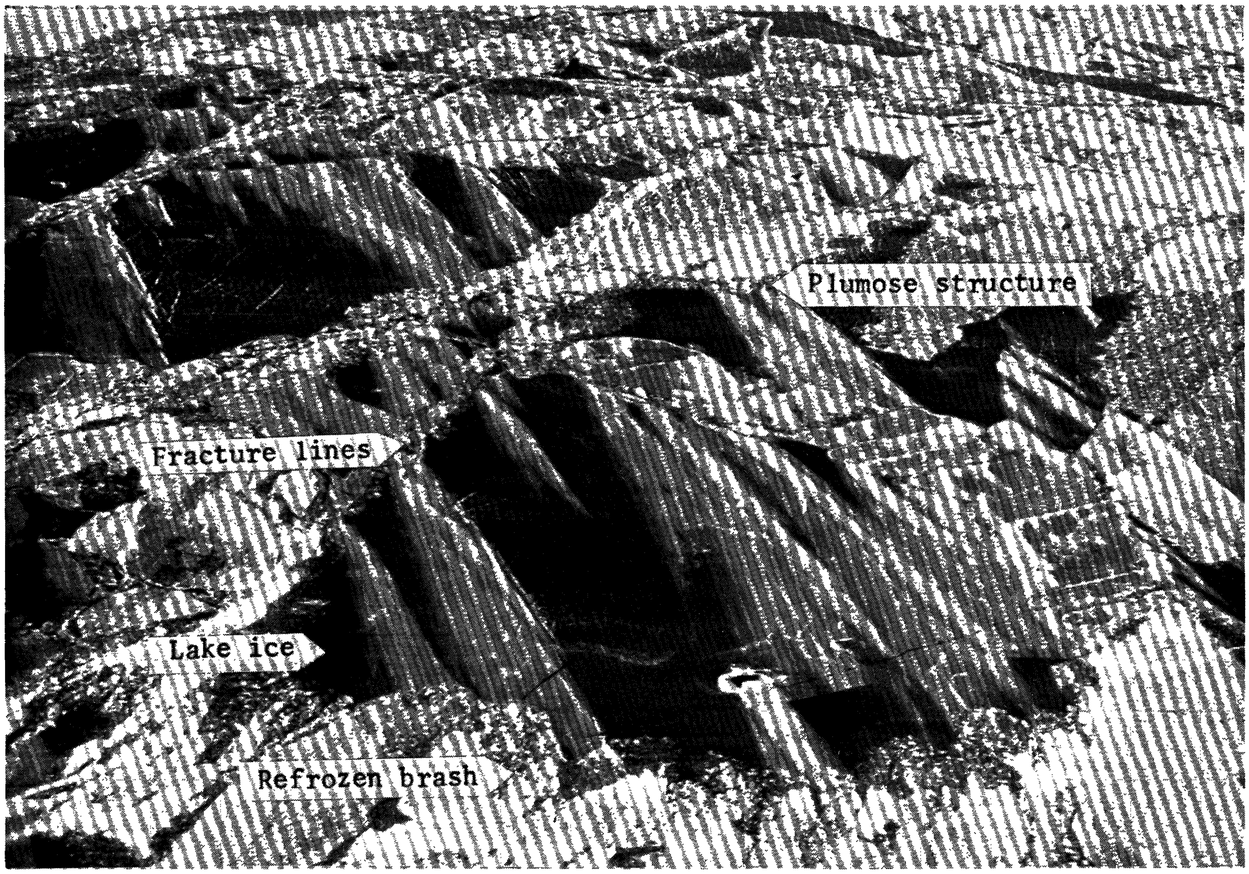

FIG. 31. WATER STREAK PATTERN RESULTING FROM WIND DIRECTION SHIFTS. In this illustration the water streaks expand from the point of origin and indicate either changes of wind direction or rotation of the ice floe. This is in contrast to Figure 30 where the streaks taper to a point. The gray albedo of the plume is in contrast to the dark lake ice and indicates the water film has frozen. Lake Erie, 2/4/65. Altitude: 800 ft.

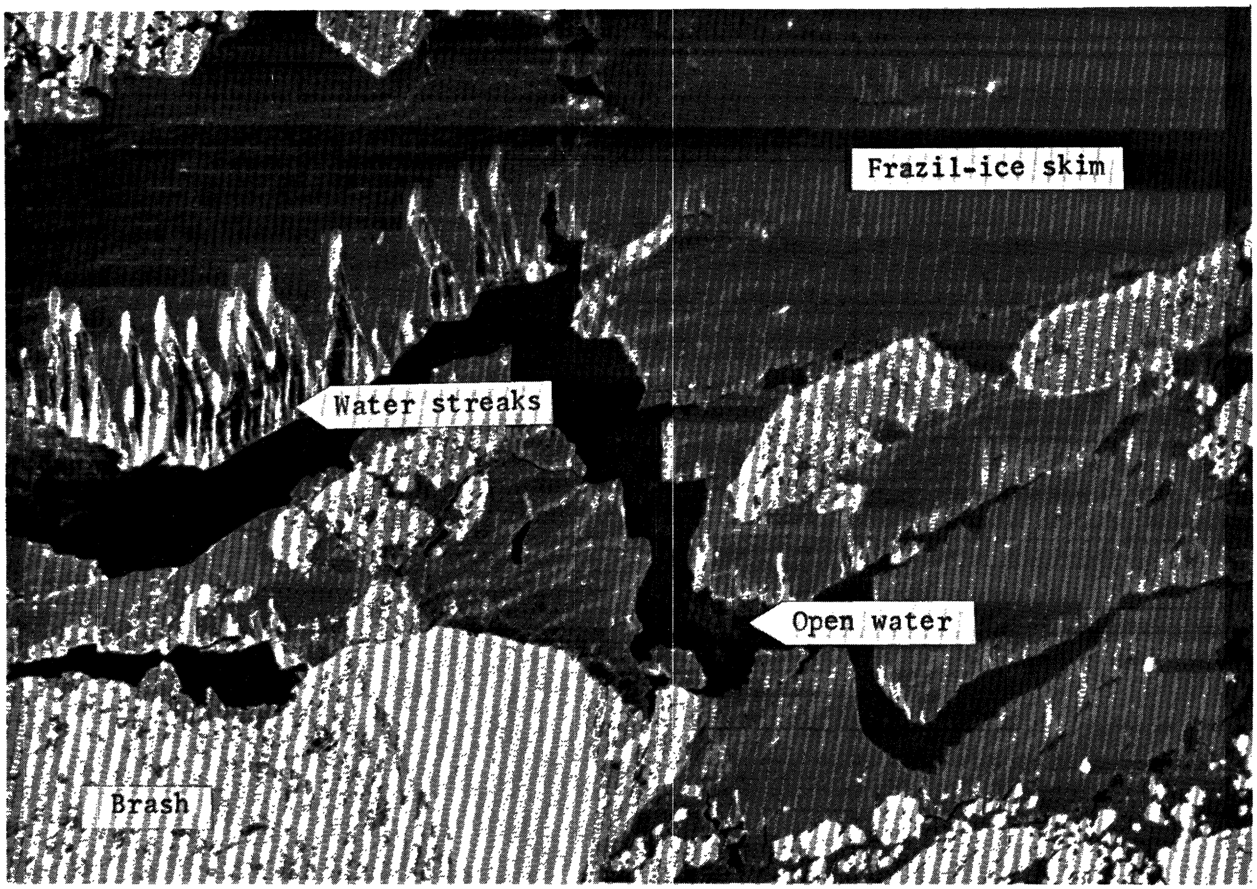

FIG. 32. WATER STREAKS LADEN WITH FRAZIL ICE. These tongue-like patterns result when the wind-blown water film becomes laden with frazil ice. The water-frazil ice mixture may blow out from the open water, or the frazil ice may form within the water film as it blows across the ice sheet. The outer ends of the tongues show a change in albedo which may result from this accumulation of frazil ice. Sudden shifts in wind direction are indicated by the orientation of the tongue. These tongues extend approximately 100-200 meters onto the ice surface. Lake Erie, Photo 9L-168-2R.

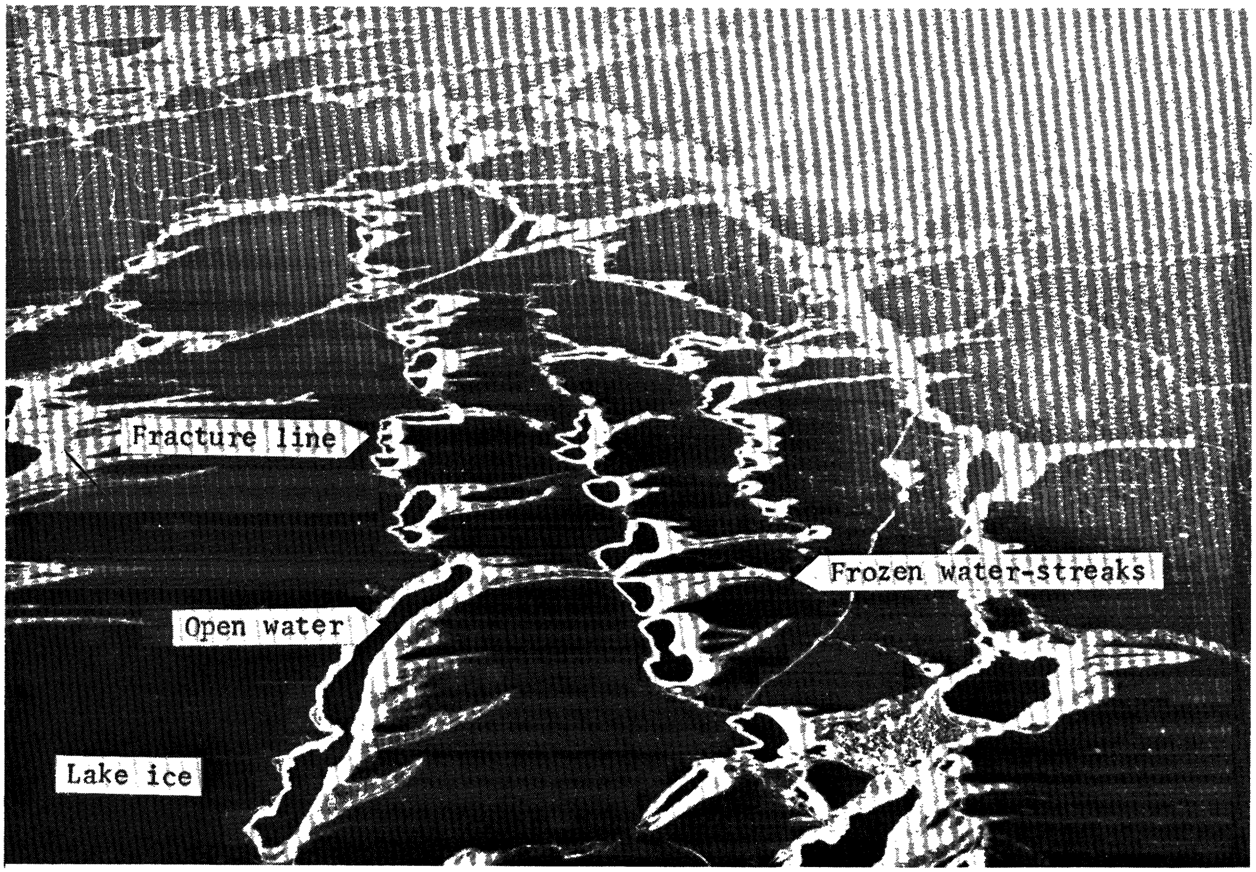

FIG. 33. IRREGULAR WATER STREAKS ORIGINATING ALONG FRACTURE LINES. Winds have caused blow-out areas along the fracture lines in an ice skin. The ice fragments resulting from the formation of these open water areas together with frozen wind-blown water streaks form a white rim around the open water. Winds blowing from the left to right formed the irregular water streaks. Lake Erie, 2/4/65. Altitude: 1500 ft.

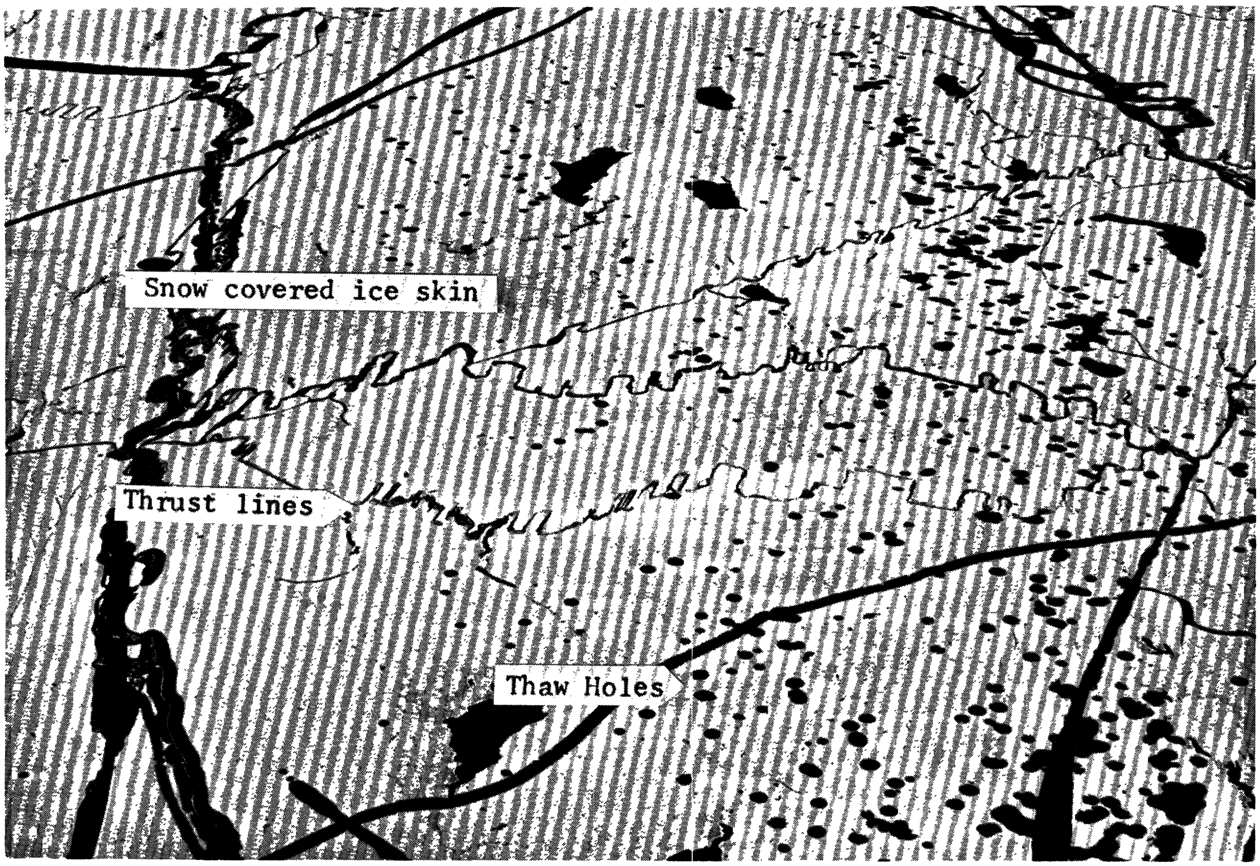

FIG. 34. THAW HOLES ON A SNOW-COVERED ICE SHEET. The black spots are points at which thawing has occurred. Lake waters have blotted into the snow cover to form the distinctive spot pattern. Reason for the localization of the thawing is unknown. The water-soaked snows reveal cracks and the distinctive, rectilinear tracery of thrust lines. Lake Erie, 2/4/65. Altitude: 1800 ft.

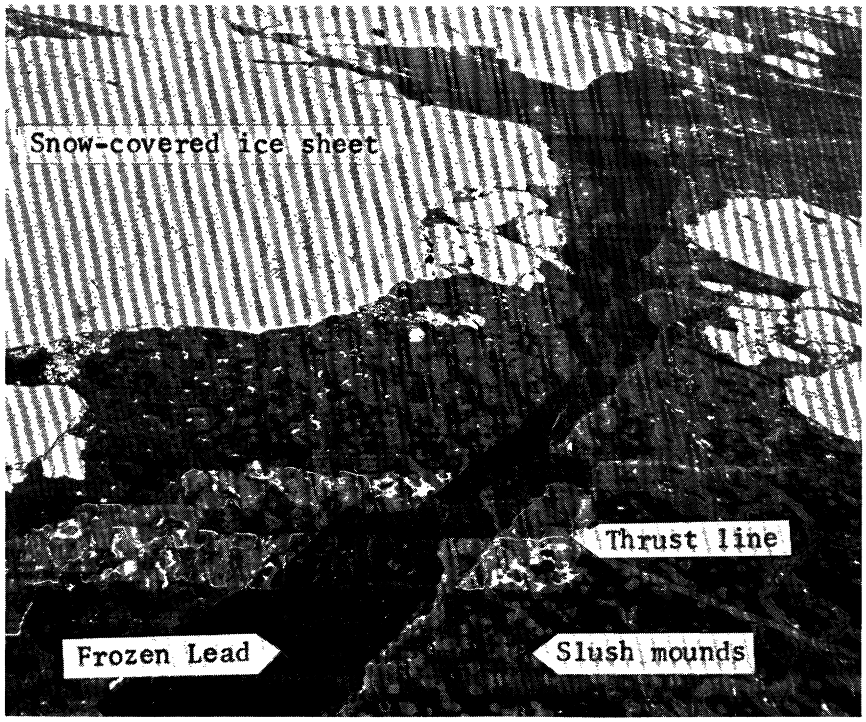

FIG. 35. FORMATION OF SNOW-ICE PATCHES. Blowing snow which collects in wet zones surrounding thaw holes and cracks is the beginning stage in the formation of snow-ice mounds and ridges. Lake Erie, 2/4/65. Altitude: 1800 ft.

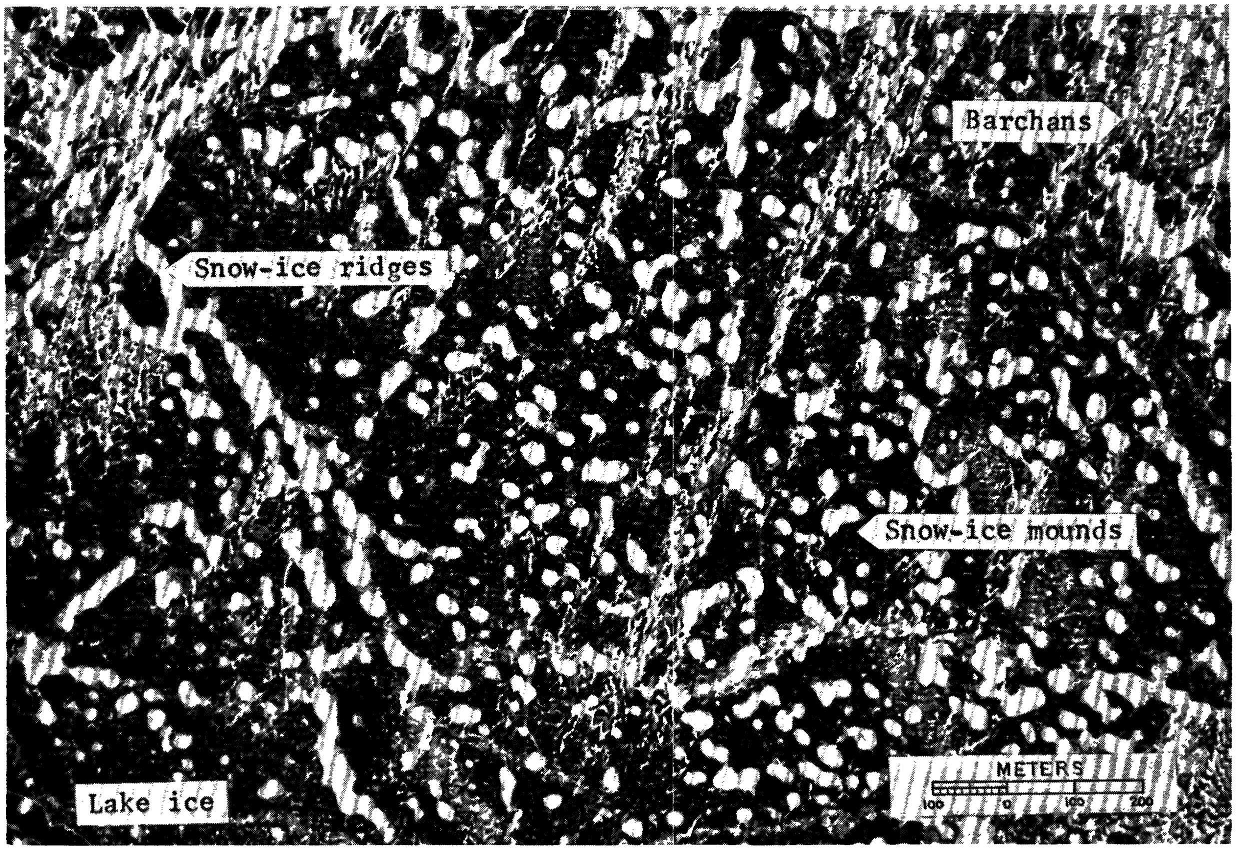

FIG. 36. SNOW-ICE PATCHES. Snow-ice patches 25-75 meters in diameter form by the process illustrated in Figure 35, where blowing snow fills the thaw holes and cracks. As the snow accumulates it acts as a wick for the lake waters. Lake Superior, Photo 9R-250-1L.

THRUST STRUCTURES

Thrust structures in lake ice were observed in aerial photographs of Great Lakes ice and on reconnaissance flights. Thrust structures in sea ice were described by Weeks and Anderson (1958). Lake ice thrust structures were observed by the writer in Lake Erie in the new ice formed in leads at the edge of fast ice and between ice floes in midlake locations.

The basic thrust pattern consists of a series of parallel rectilinear overthrusts alternating with similarly shaped underthrusts. The maximum dimension of the thrust units is usually perpendicular to the initial ice edge. In these respects it is similar to sea-ice thrust structures.

The lake ice thrusts occurred in newly formed homogeneous frazil ice skims and lake ice skins as well as in inhomogeneous ice sheets of refrozen brash and in ice sheets surfaced with snow ice.

Thrust lines up to 14 kilometers in length were observed in refrozen leads. On vertical aerial photographs where measurements could be made, the widths of individual rectilinear thrust units ranged from approximately 33 to 220 m while the length of overthrusts extended up to 412 m.

The thrust pattern can be related to ice type and thickness. Thrust patterns in frazil ice are characterized by a jagged thrust line where individual thrust units are irregular and poorly defined (Fig. 37). The frazil ice skim, a few millimeters in thickness and felt-like in structure, is incompetent to transmit the forces. Thrust patterns in harder and thicker ice skins are characterized by clearly defined rectilinear thrust units (Fig. 38). When thrusting occurs in a new ice skin lightly covered by snow, the pattern is strikingly delineated by water which has soaked into the snowpack (Fig. 39). The basic thrust pattern is not affected by the structure of the ice sheet once the sheet is frozen into a hard, competent layer. The inhomogeneities produced by snow ice, refrozen brash, and refrozen fractured ice merely serve to create a rounded appearance to the individual thrust units (Figs. 40, 41, 42). This suggests that there may be a sequence of patterns from the distinct ones formed in thin ice skins to the gently scalloped, indistinct patterns of crushing associated with pressure ridges in thick ice sheets. This may provide a criterion by which ice thickness may be determined from aerial observation.

Aerial photos show fine lineations running across the individual thrust units at right angles to the direction of thrust (Fig. 40). These lineations are believed to represent small open folds

similar to features observed by Weeks and Anderson (1958) in sea ice. The spacing of these lineations may be another criterion for determining ice thickness.

In sea ice, brines drain from the loose interlocking plate-like structure and provide a continuous film of concentrated brine between the thrust plates. In lake ice such a water film cannot be produced from the ice sheet. However, features in Figure 38 suggest that under certain circumstances water films may exist between the ice plates. In this figure, the lighter tone of some individual thrust units indicates that a slight air space exists between the overthrust and underthrust units. The darker toned units have water films between them. Whether this water film was carried forward from the thrust line during thrusting or entered from the open lead after the thrusting cannot be determined. It is believed, however, that lubricating films are not necessary to the formation of lake ice thrusts due to the low frictional resistance between hard, thin lake ice skins at temperatures close to freezing.

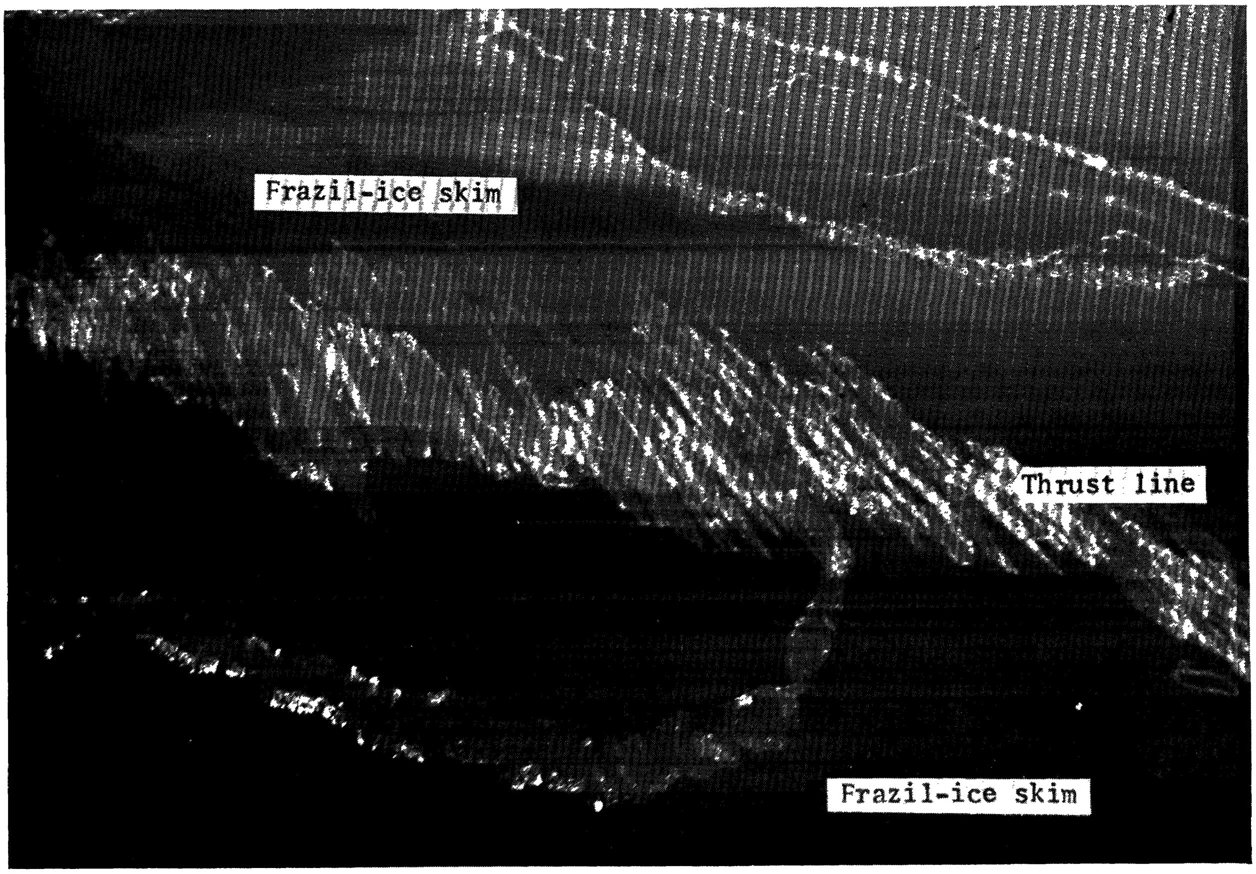

FIG. 37. THRUST PATTERN IN FRAZIL ICE SKIM. Thrust patterns in a frazil ice skim are characterized by a jagged thrust line where the individual thrust units are irregular and poorly defined since the ice skim is structurally incompetent. Lake Erie, 1/21/65. Altitude: 1500 ft.

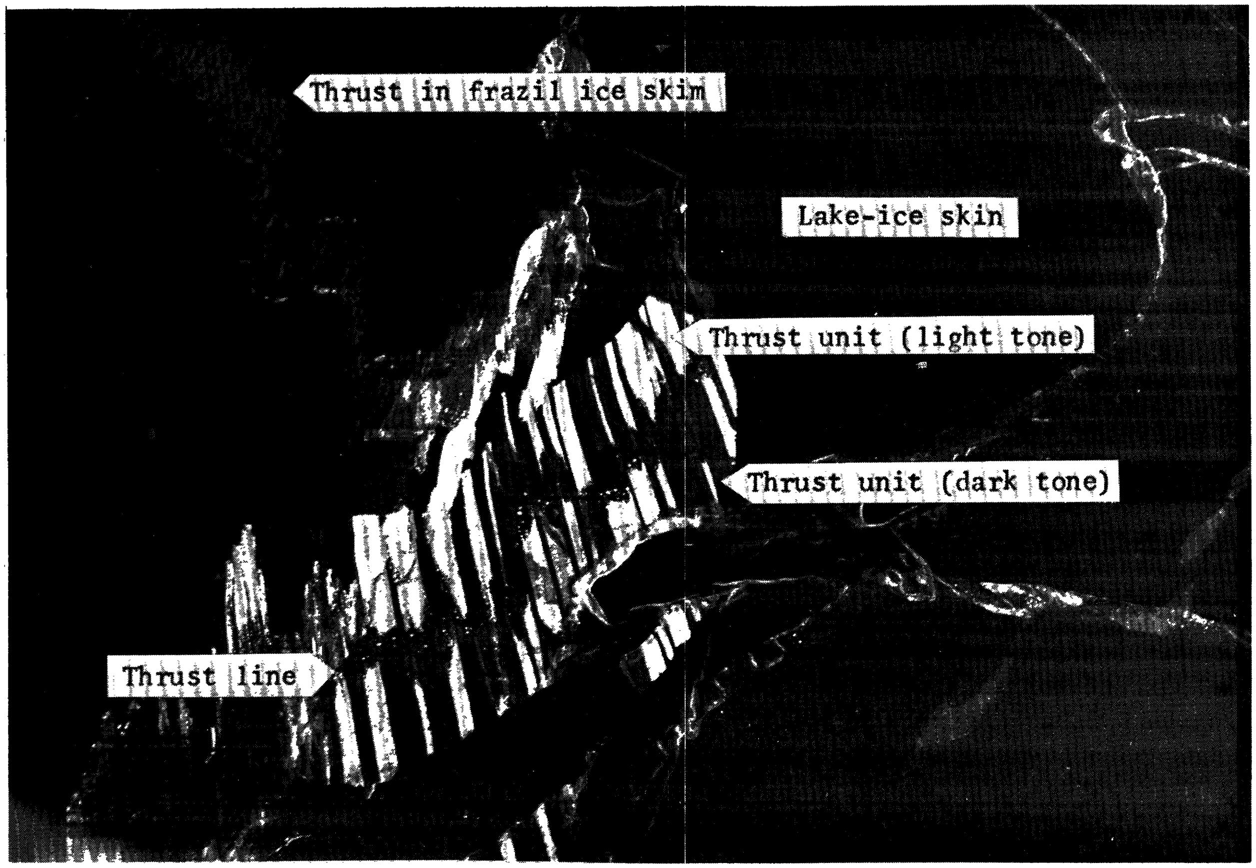

FIG. 38. DETAIL OF A THRUST PATTERN IN A NEW ICE SKIN. The thrust pattern in a homogeneous new ice skin is characterized by clearly defined rectilinear thrust units. This is in contrast to poorly defined patterns of a frazil ice skim in the upper left. The ligher tone to some of the individual thrust units suggests that an air space exists between the thrust plates. The darker toned units are believed to have a water film between them. Lake Erie, 2/4/65. Altitude: 1500 ft.

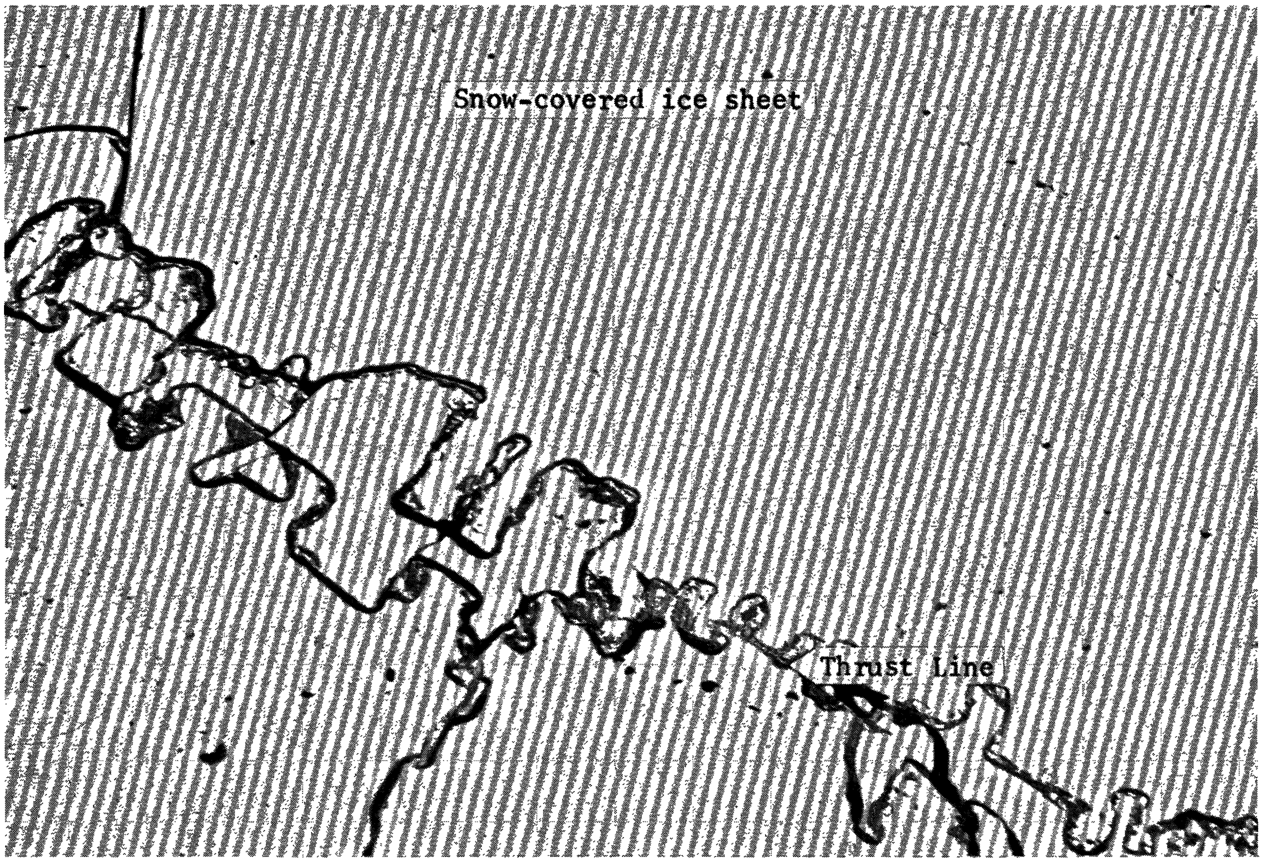

FIG. 39. THRUST PATTERN IN A SNOW-COVERED NEW ICE SKIN. The thrust pattern is delineated by water soaking up into the snowpack. Lake Erie, 2/4/65. Altitude: 1800 ft.

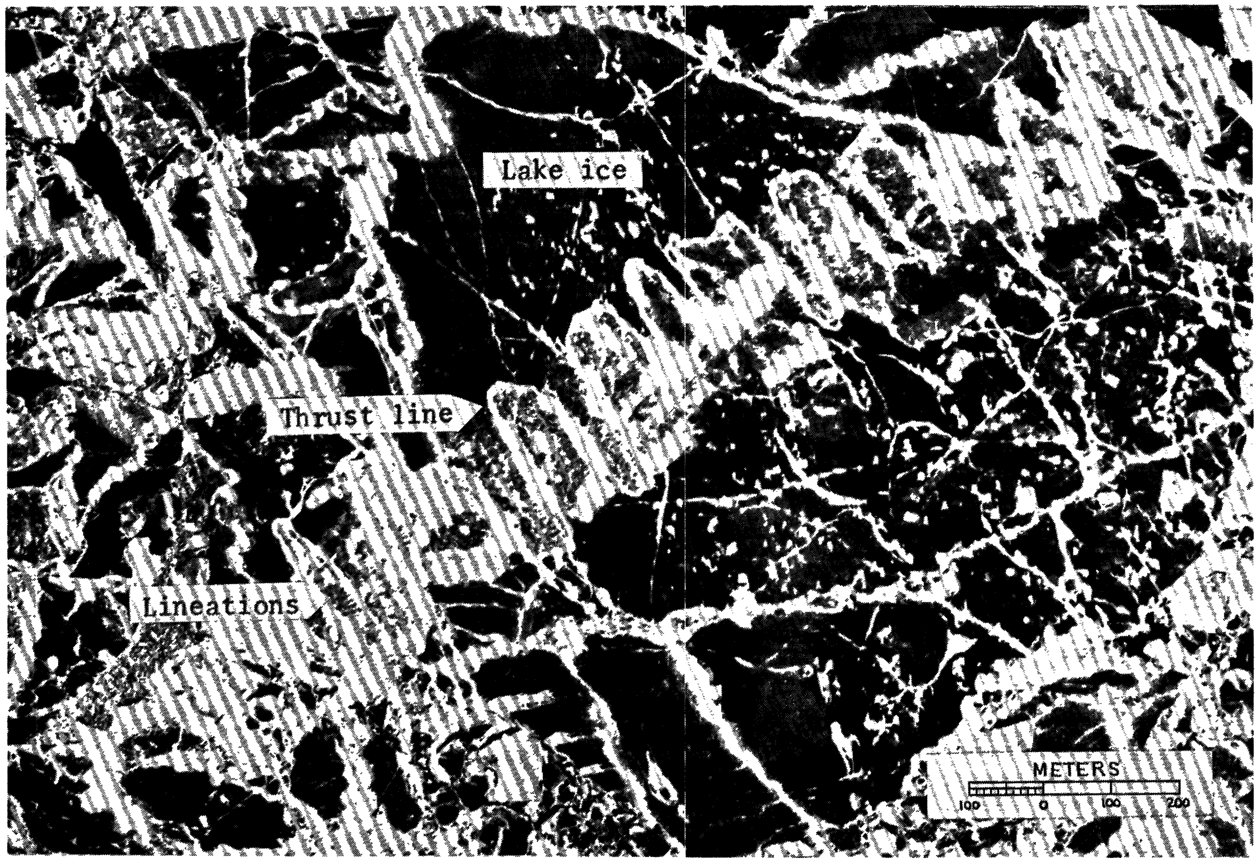

FIG. 40. THRUST PATTERN IN A SHEET OF LAKE ICE. In this example of thrusting in a sheet of lake ice, the length of overthrust ranges from 207 to 272 meters with the widths of the individual thrust units ranging from 40 to 157 meters. Fine lineations are seen running across the individual thrust units at right angles to the direction of thrusting. These lineations are believed to represent small open folds. Lake Erie, Photo 9R-336-V.

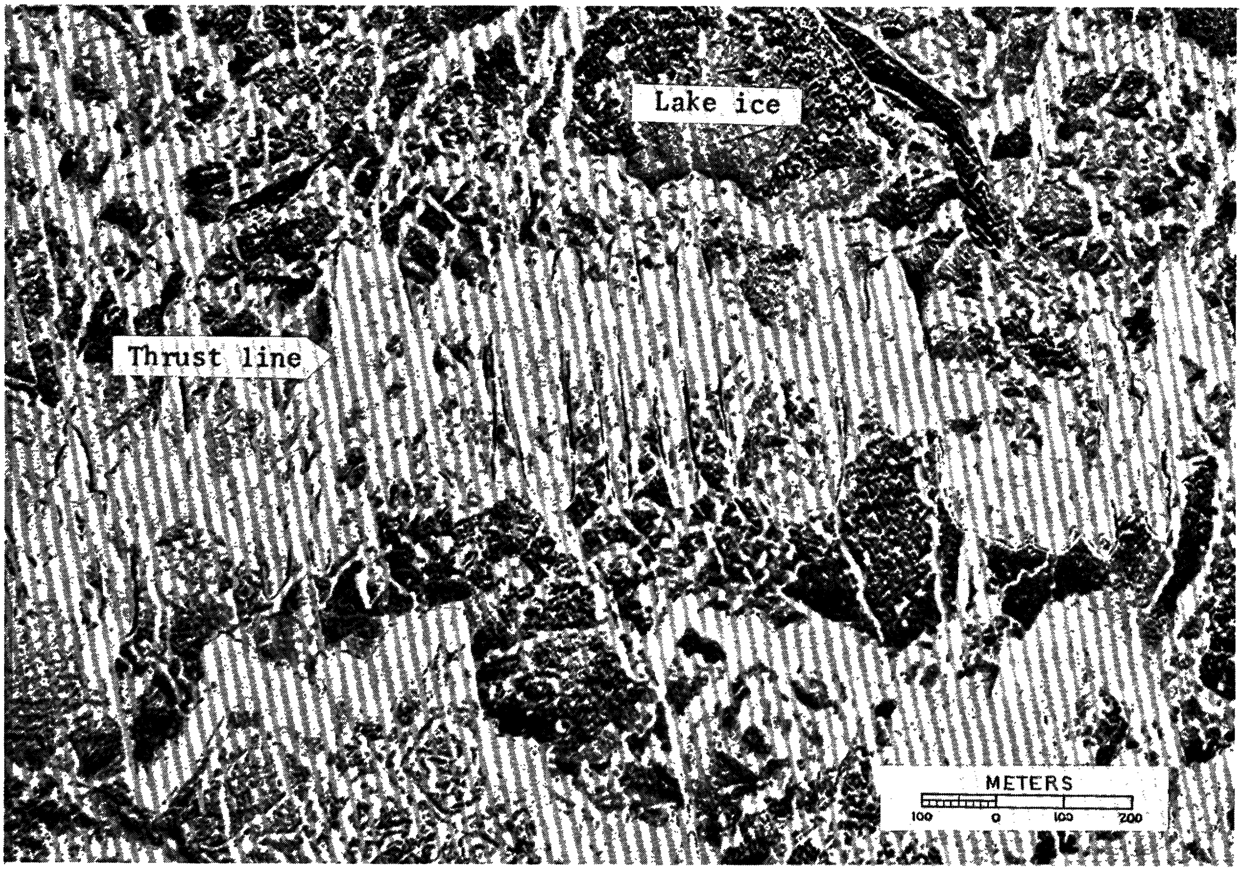

FIG. 41. OVERTHRUSTS IN A FRACTURED LAKE-ICE SHEET. In this case the length of overthrust ranges from 334 to 412 meters with the widths of the individual thrust units ranging from 33 to 220 meters. This ice sheet is inhomogeneous in that areas of the overthrust were fractured and refrozen before this complex thrusting. Lake Erie, Photo 9L-446-V.

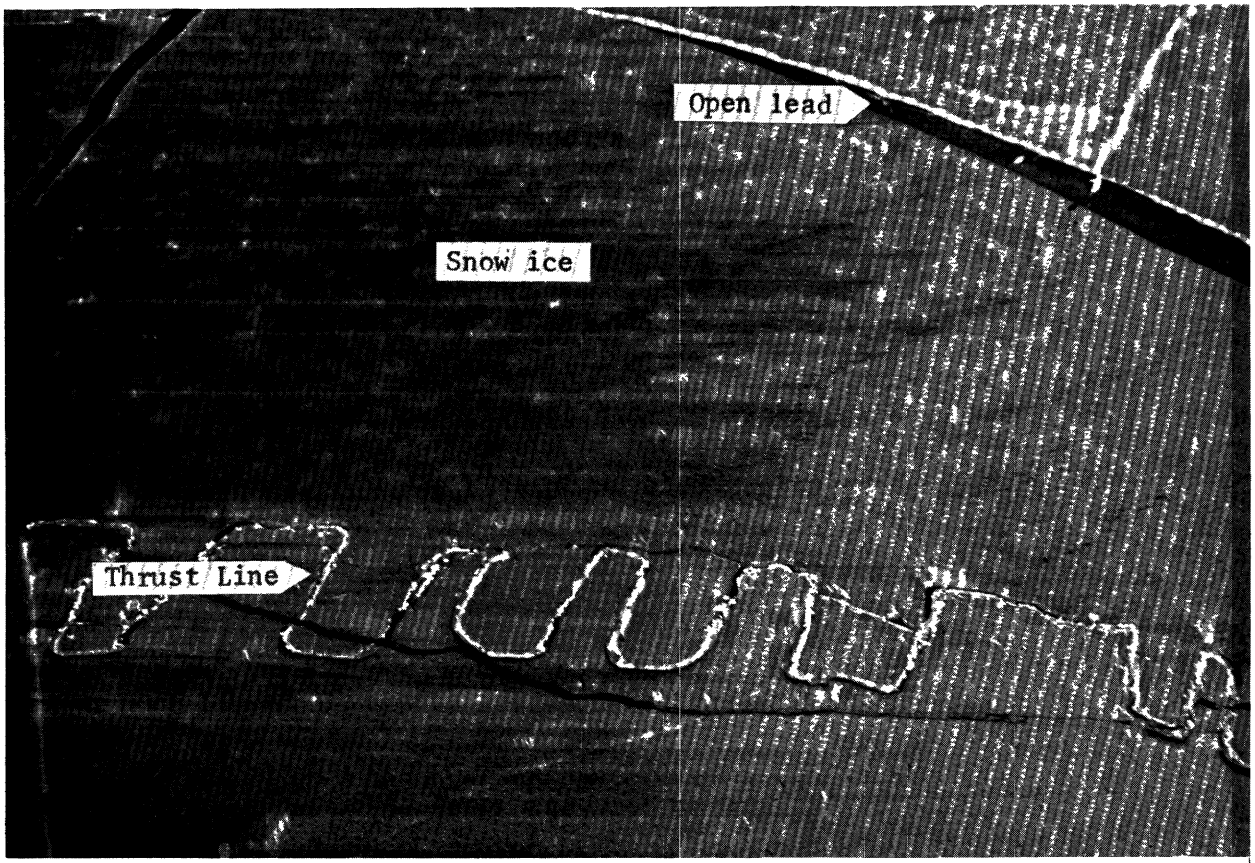

FIG. 42. THRUST PATTERN IN AN ICE SHEET WITH A SNOW-ICE SURFACE LAYER. This is an example of thrusting in an inhomogeneous ice sheet where the surface layer is composed of snow ice. The principal effect of inhomogeneities as seen in Figures 40 and 41 is to create a rounded appearance to the individual thrust units in contrast to the sharp, rectilinear pattern of homogeneous ice skins. Lake Erie, 2/4/65. Altitude: 1800 ft.

ICE SHEET FEATURES

The ice observed in Great Lakes floes consisted of two basic types, lake ice and snow ice, each of which has a distinctive pattern.

Lake ice forms by the freezing of lake waters and is composed of an aggregate of roughly columnar crystals, the long dimensions of which form at right angles to the freezing surface. A general characteristic of the structure is for certain crystals to increase in size with ice sheet thickness while others pinch out at depth. Little quantitative information is available on crystal size in Great Lakes ice sheets; however, the writer's investigation on inland lakes indicated that crystal diameters at the surface can range from a few millimeters to nearly one meter.

The albedo of a sheet of lake ice is very low, since the sheet is relatively transparent and floats on the dark lake waters (Figs. 38, 40); however, later crushing and fracturing of the ice increases the albedo.

Snow ice can form in several ways: by snow falling onto a still water surface at the time of freeze-up, by the depressing of an ice sheet by snow loading, by water soaking into the snowpack through fractures and thermal contraction cracks, and by thawing and refreezing of the snowpack during winter and spring thaws. Snow ice is granular in structure with grain diameters ranging from a few millimeters to one centimeter. Each of these methods of snow-ice formation is found in various environments of the Great Lakes.

When snow falls onto a water surface, a slush layer is formed which freezes to form a fine grained snow ice. This method of snow-ice formation occurs most frequently in the still water areas of open leads (Figs. 9, 43, 44). Once the snow ice is frozen, lake ice forms under it to produce an ice sheet compound in structure. Where snows fall on areas of open water, turbulence stirs the slush layer or molds it into ball ice (Figs. 15, 19).

The formation of snow ice by snow loading occurs in protected bays and coves. In these areas the accumulated weight of snow is sufficient to depress the ice sheet and allow lake waters to soak into the snow which later freezes to form snow ice. Snow ice also forms where wind-blown snows catch along fractures in the ice sheet. Snow dunes on Lake St. Clair were observed to change into snow ice during February thaws and freezes.

Both lake-ice and snow-ice sheets can be broken by wave action or squeezed by pack pressures to form brash and ridged ice which refreezes and may break into ice floes (Figs. 45, 56).

Ice sheets exhibit varying degrees of physical breakup of the ice sheet throughout the winter. This varies from crack formation to a complete physical break-up and comminution of the ice sheet. Cracks in new ice skins catch blowing snow and begin the formation of distinctive snow-ice ridges (Figs. 47-50).

Wave action on fast ice or on ice floes causes simple and complex crack patterns. Where waves flex the edge of fast ice the resulting parallel cracks produce long linear ice floes (Figs. 51, 52). When drifting floes are flexed by wave action a complex pattern of cracking is produced (Fig. 53). The physical break-up of an ice sheet of this type produces a fine textured brash. If the cracks refreeze, a unique pattern is produced in the ice sheet (Fig. 54). The ice sheet is broken into larger cakes where the water turbulence is less severe (Figs. 55, 56).

Winds blowing across loose brash ice form it into fields composed of long narrow brash belts. These belts are composed of streamlined patches of brash aligned with the wind and streaming very narrow belts of brash behind them (Figs. 57, 58).

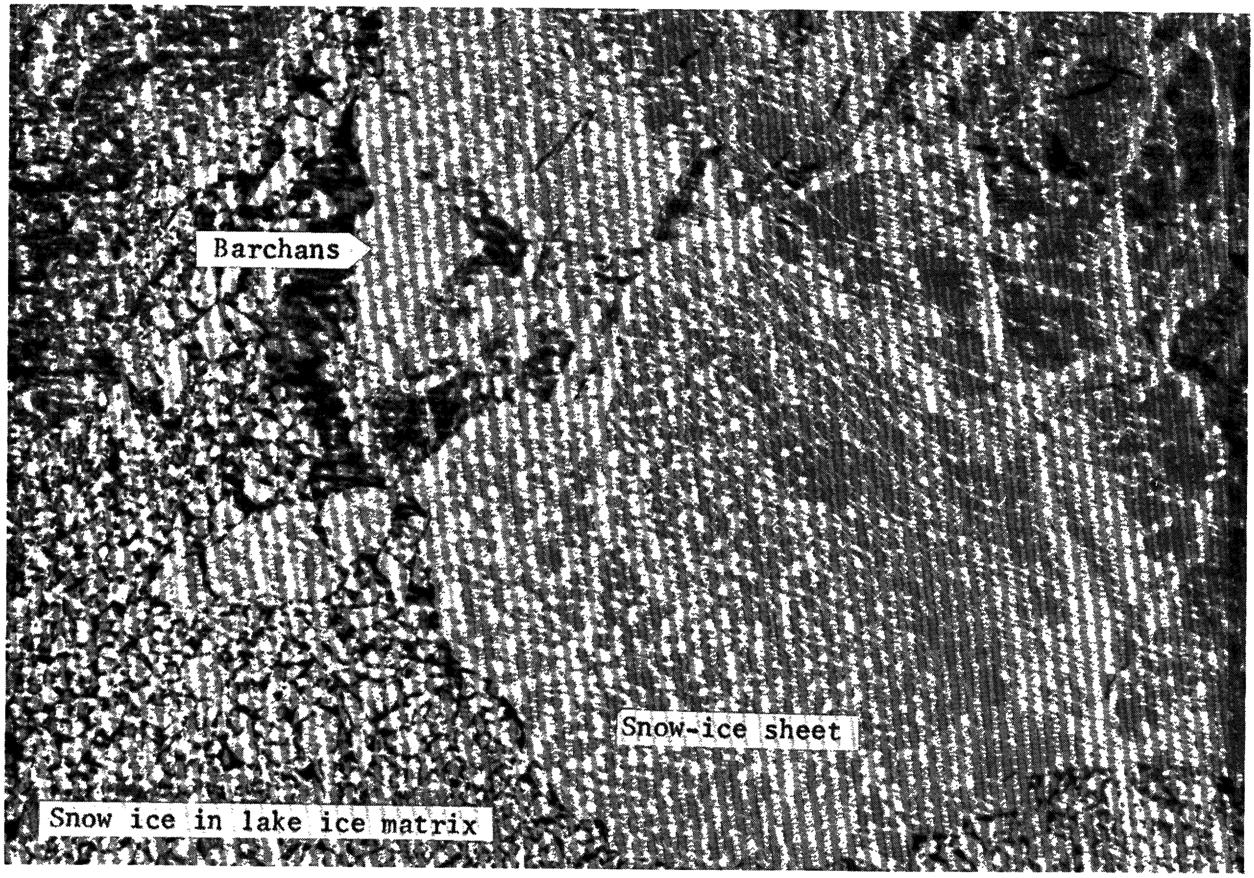

FIG. 43. SNOW-ICE FLOE. The snow ice (light gray tone) originated as a slush layer on the water surface. Portions of the snow-ice floe have undergone physical break-up and the fragments are frozen in a matrix of lake ice (black). Crescent shaped snow dunes (barchans) mantle the whole lake-ice surface. Lake Huron, Photo 9R-275-1L.

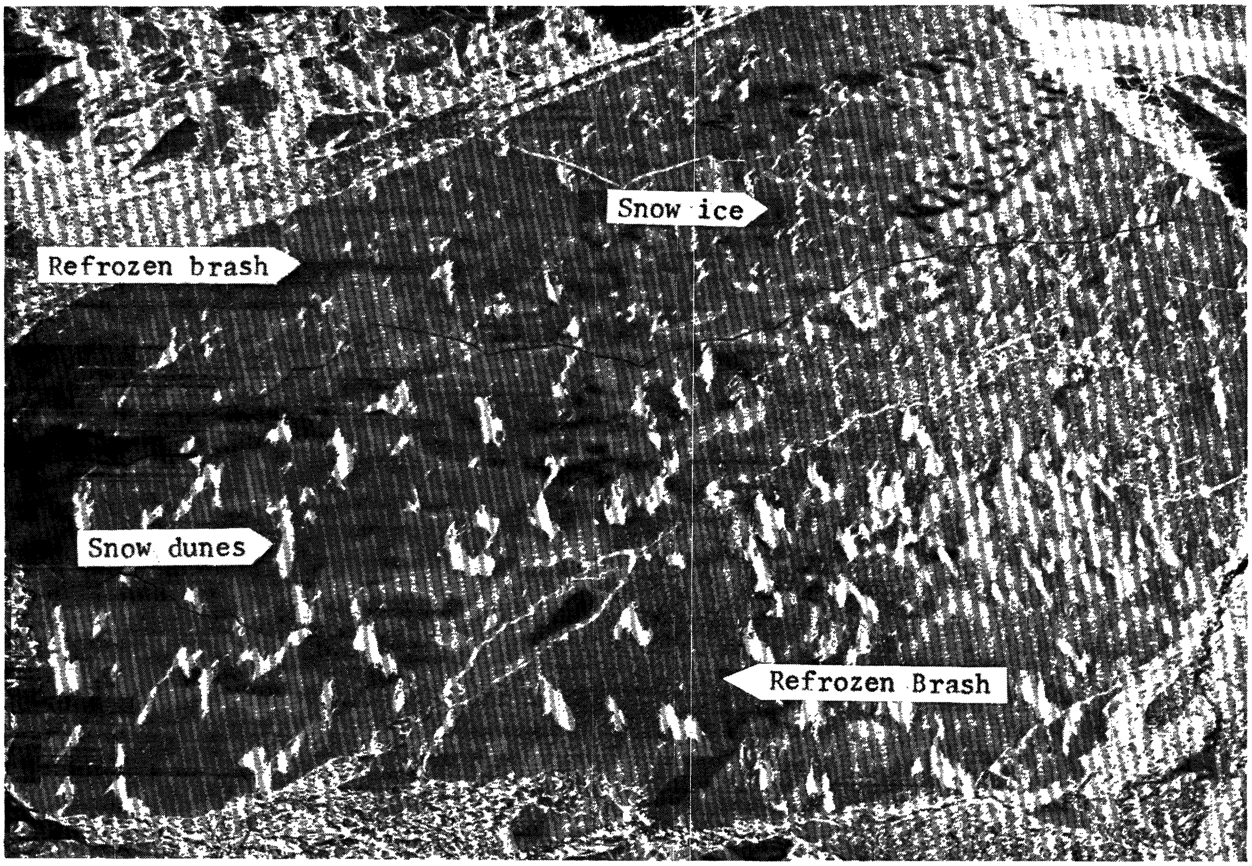

FIG. 44. SNOW-ICE AND BRASH-ICE FLOE. The outer edges of this floe are composed of refrozen brash while the center zone is snow ice. Snow dunes mantle the ice floe surface. Lake Erie, 2/4/65. Altitude: 1500 ft.

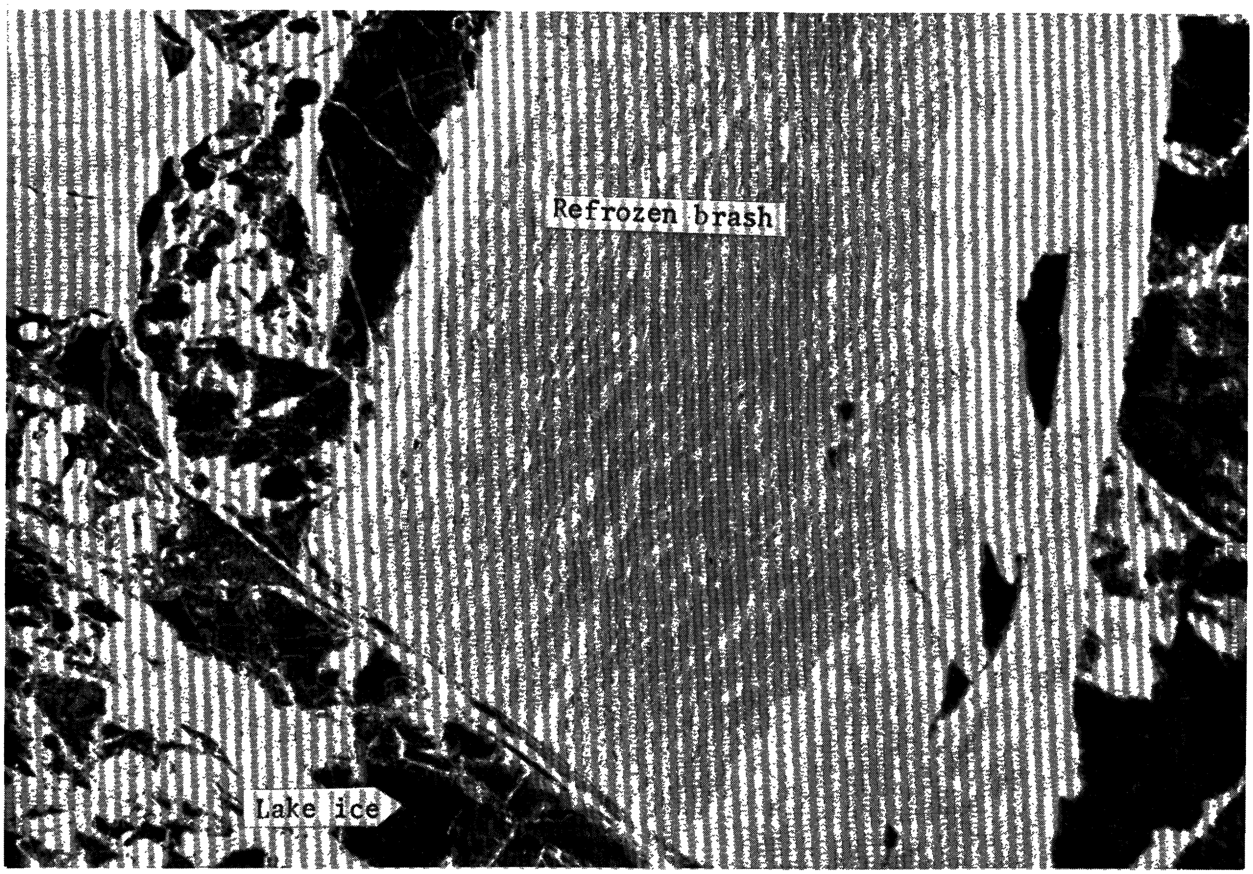

FIG. 45. A FLOE OF REFROZEN BRASH. The flowline pattern was produced by the action of winds and currents on the loose brash before freezing. The black toned areas are lake ice. Lake Erie, Photo 9L-370-1L.

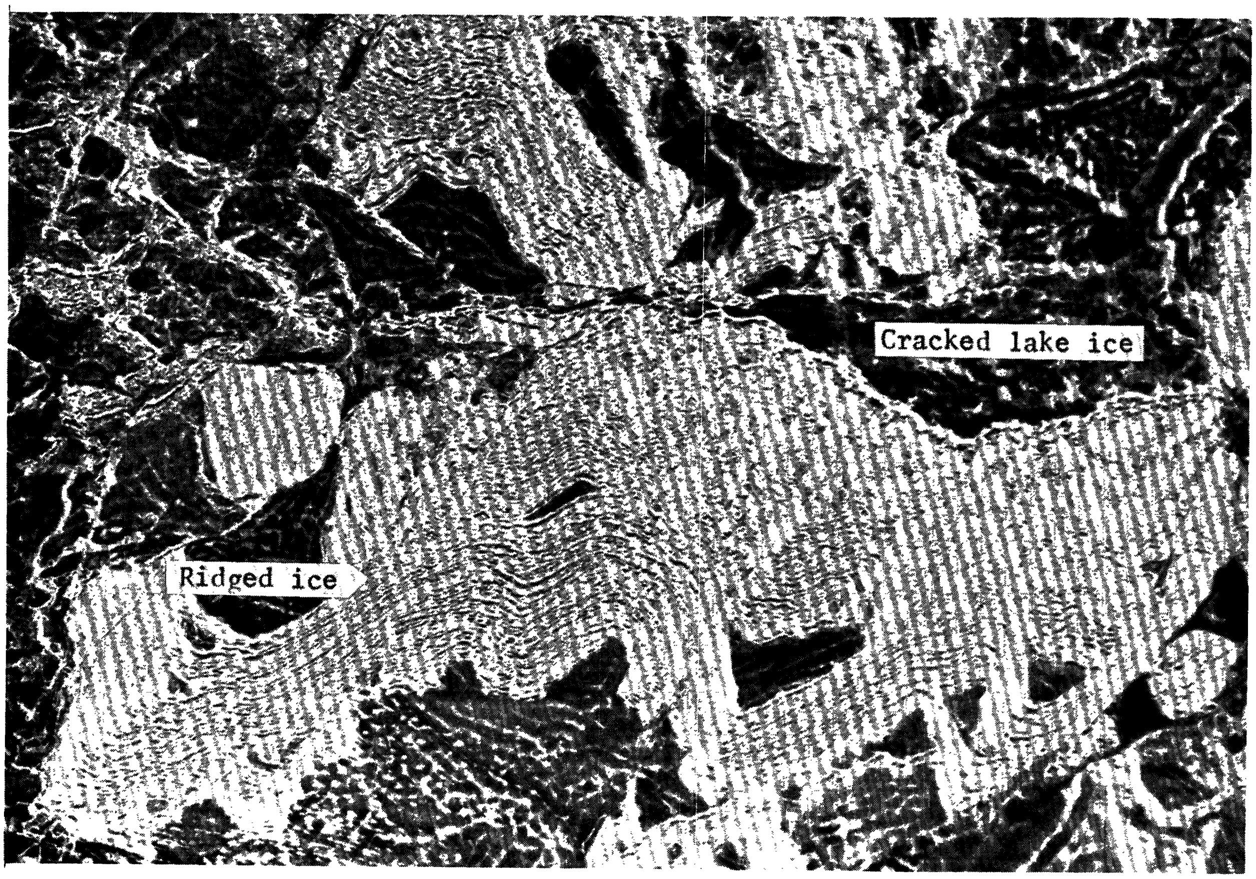

FIG. 46. RIDGED ICE. Festoons of ridged ice similar to those in the above photograph were observed on ice reconnaissance flights over Lake Erie where thin ice estimated to be less than 5 cm was pressured between heavier ice floes. Lake Huron, Photo 9R-175-1L.

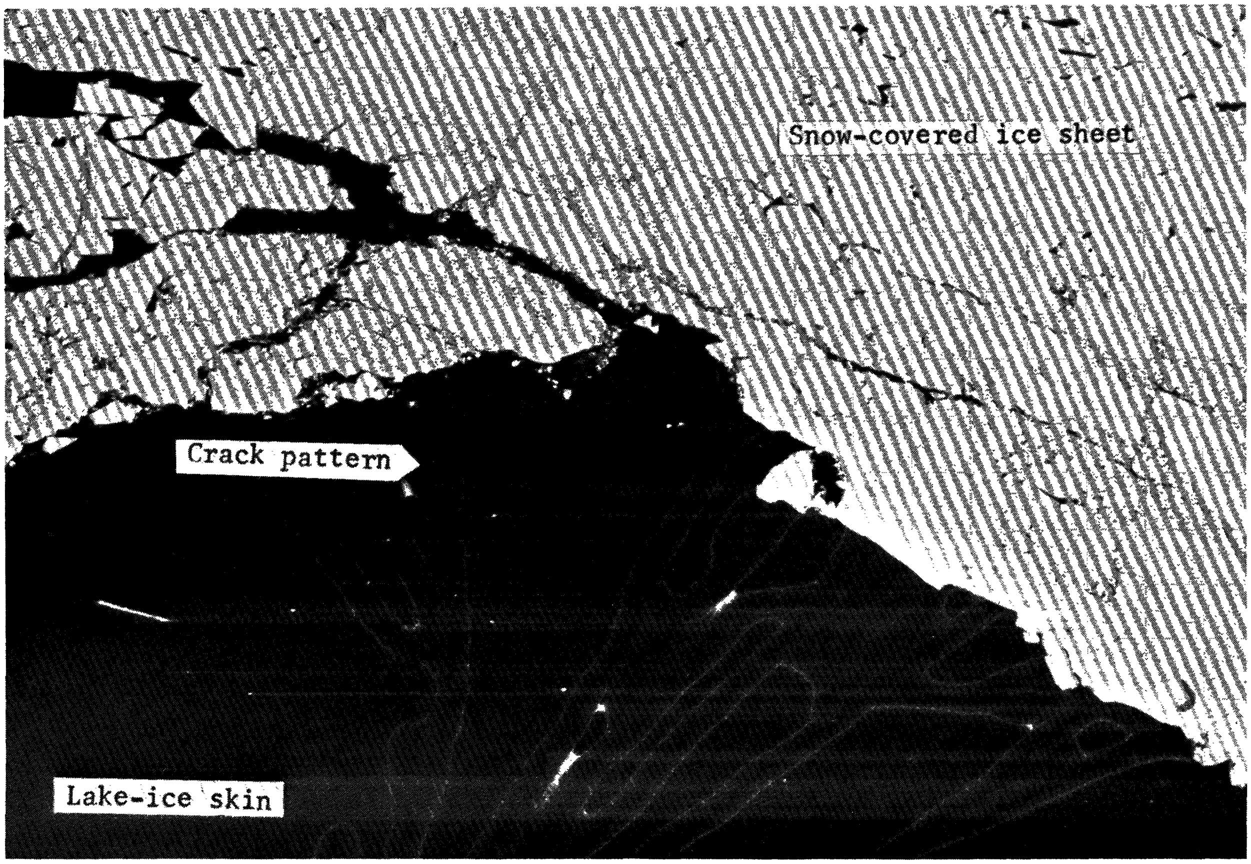

FIG. 47. CRACK PATTERN IN A THIN NEW ICE SKIN. The crack pattern is made visible by blowing snows caught in the water film which has welled up along the cracks and has spread out on either side. Snow-ice ridges form by this process. Lake Erie, 2/4/65. Altitude: 1500 ft.

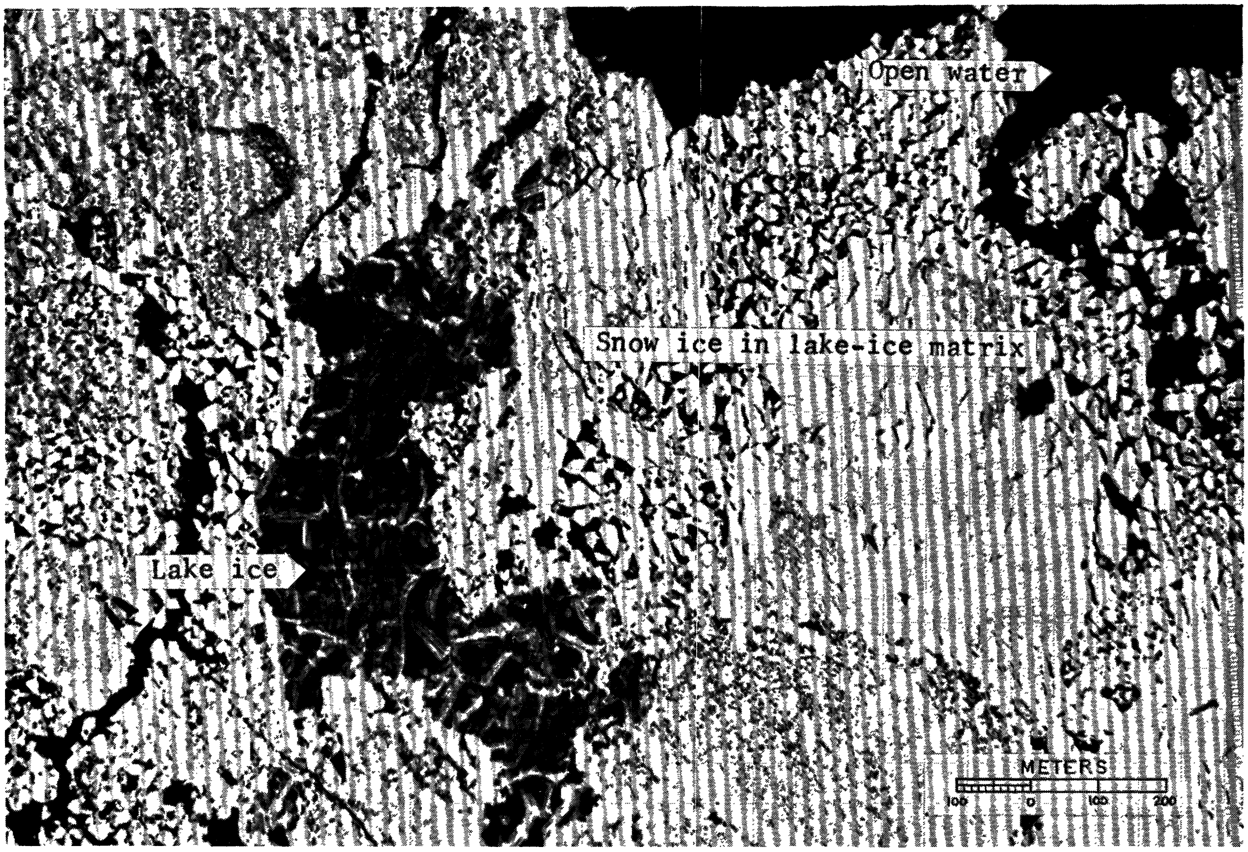

FIG. 48. FORMATION OF SNOW-ICE RIDGES. This high altitude aerial photograph shows features similar to the ones in Figure 47. Wind-blown snow has accumulated along the crack pattern in the sheet of lake ice. The surrounding ice sheet is in the process of physical break-up. Lake Huron, Photo 9R-286-V.

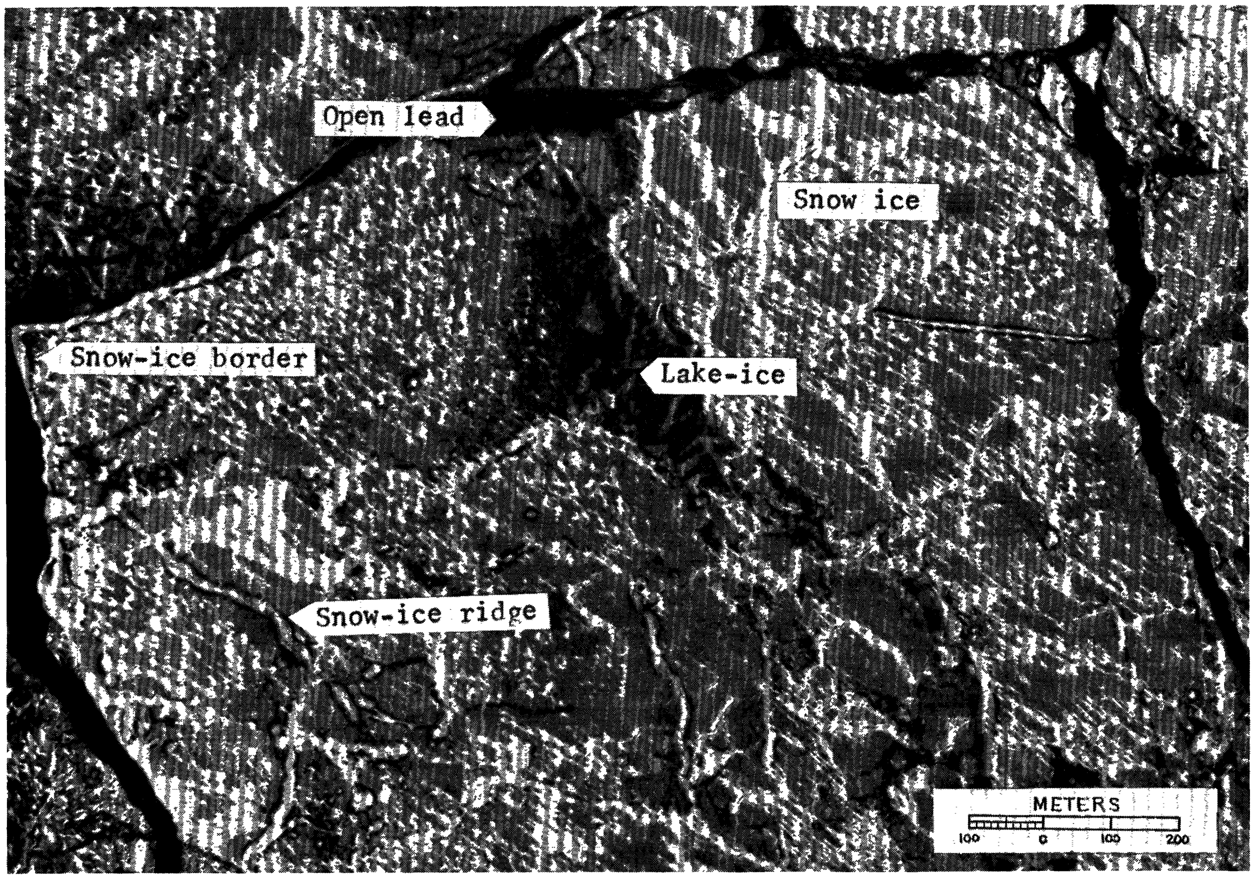

FIG. 49. SNOW-ICE RIDGES ON A SNOW-ICE FLOE. Snow-ice ridges lining former cracks are made visible by a thin, black toned lake ice border. The snow ice in this floe originated as a slush layer on the water surface and lake ice accreted under it. Cracks formed in this compound-structure ice sheet, water welled up and spread out on either side of the crack melting the gray-white, snow-ice layer. Wind-blown snows caught in this wet zone and formed narrow snow-ice ridges in this zone of black-toned lake ice. A snow-ice border has also built up in the open water on the leeward side of the floe. Lake Huron, Photo 9L-221-V.

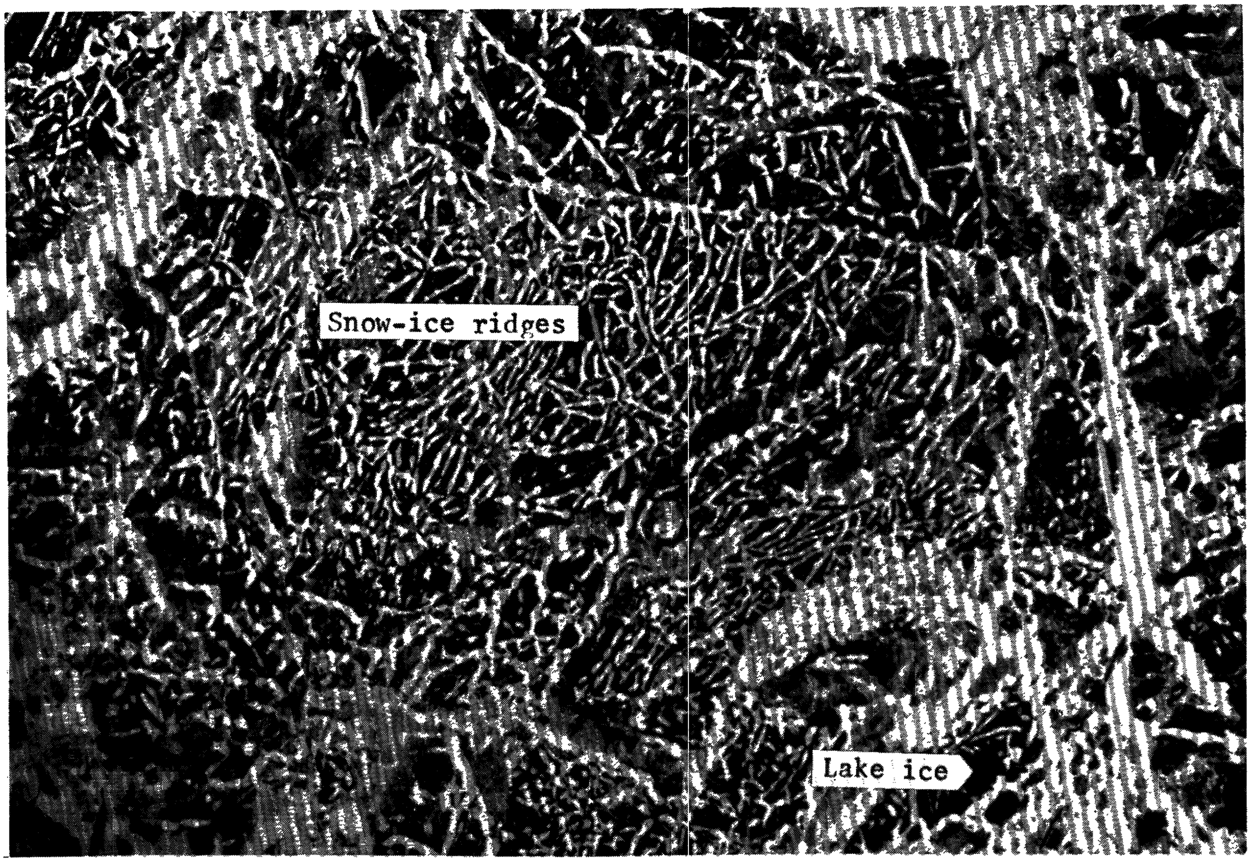

FIG. 50. SNOW-ICE RIDGES ON A SHEET OF LAKE ICE. Snow-ice ridges have formed along the crack system in a sheet of lake ice. Lake Huron, Photo 9L-110-1L.

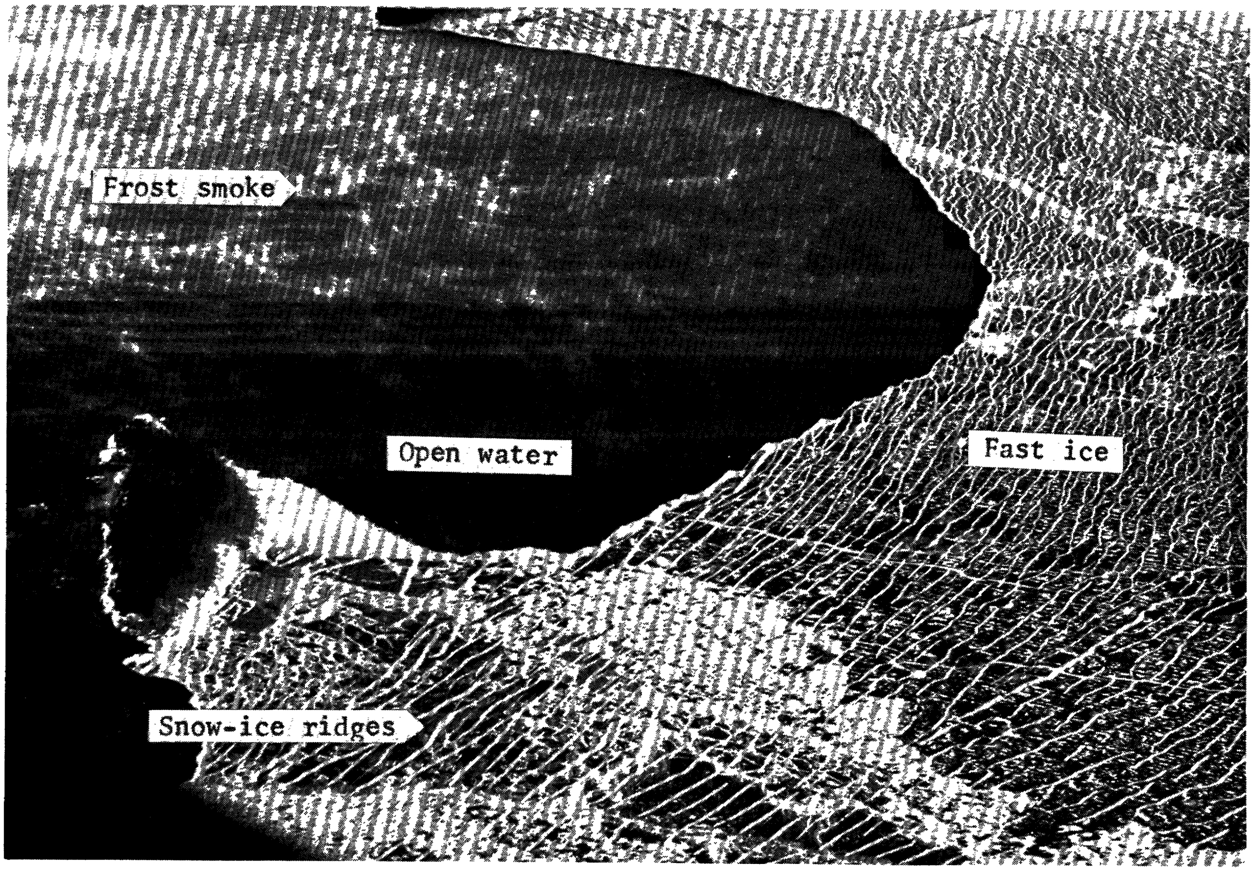

FIG. 51. CRACK PATTERN IN FAST ICE RESULTING FROM WAVE ACTION. The subparallel cracks result from waves which cause flexures in the ice sheet. Snow ice has formed along the crack system. Frost smoke is seen rising from the water surface. Lake Superior, 1/28/65. Altitude: 1000 ft.

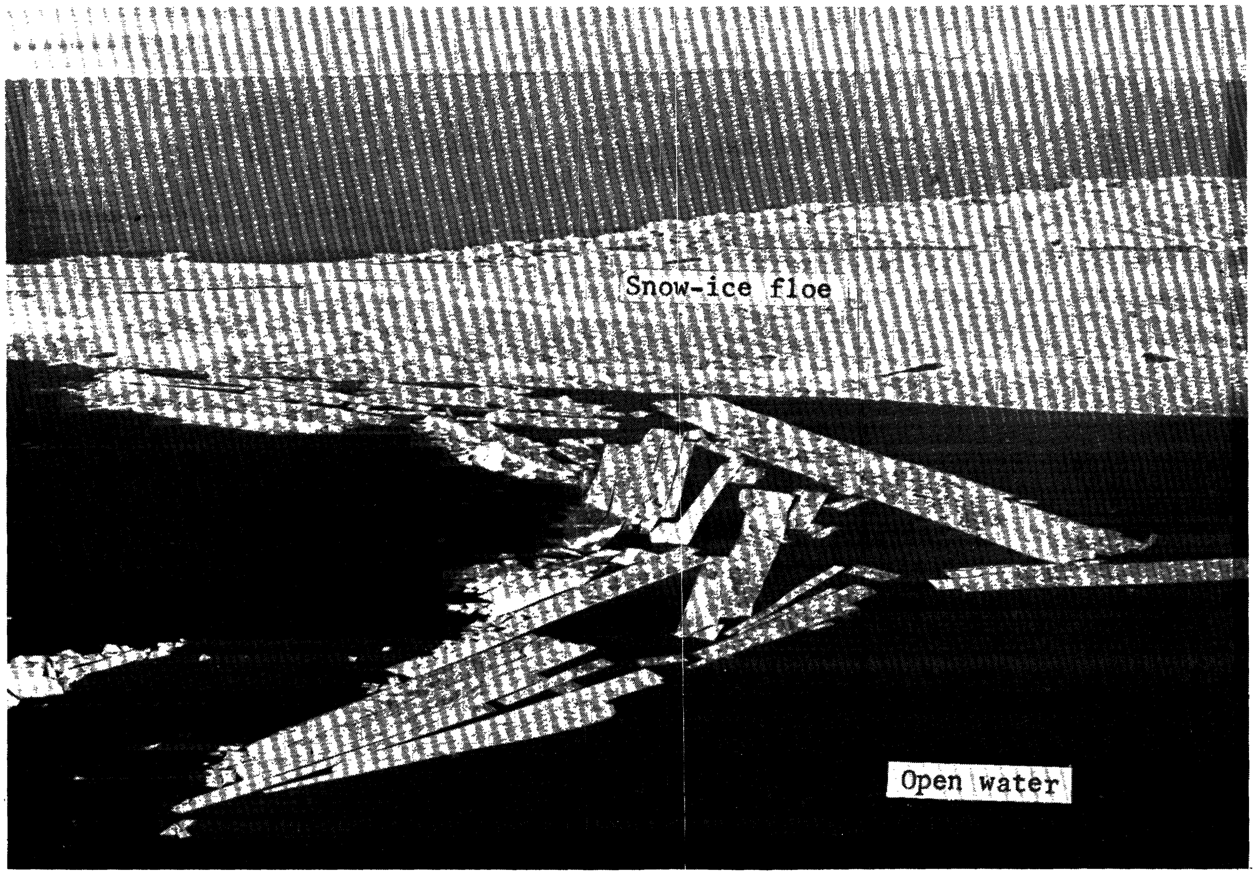

FIG. 52. PARALLEL CRACKING CAUSED BY WAVE ACTION. This floe had recently broken away from a fast ice area where the ice sheet had been flexed by wave action. Long rectangular floes were calving away from the large floe. Lake Huron, 2/5/65. Altitude: 2000 ft.

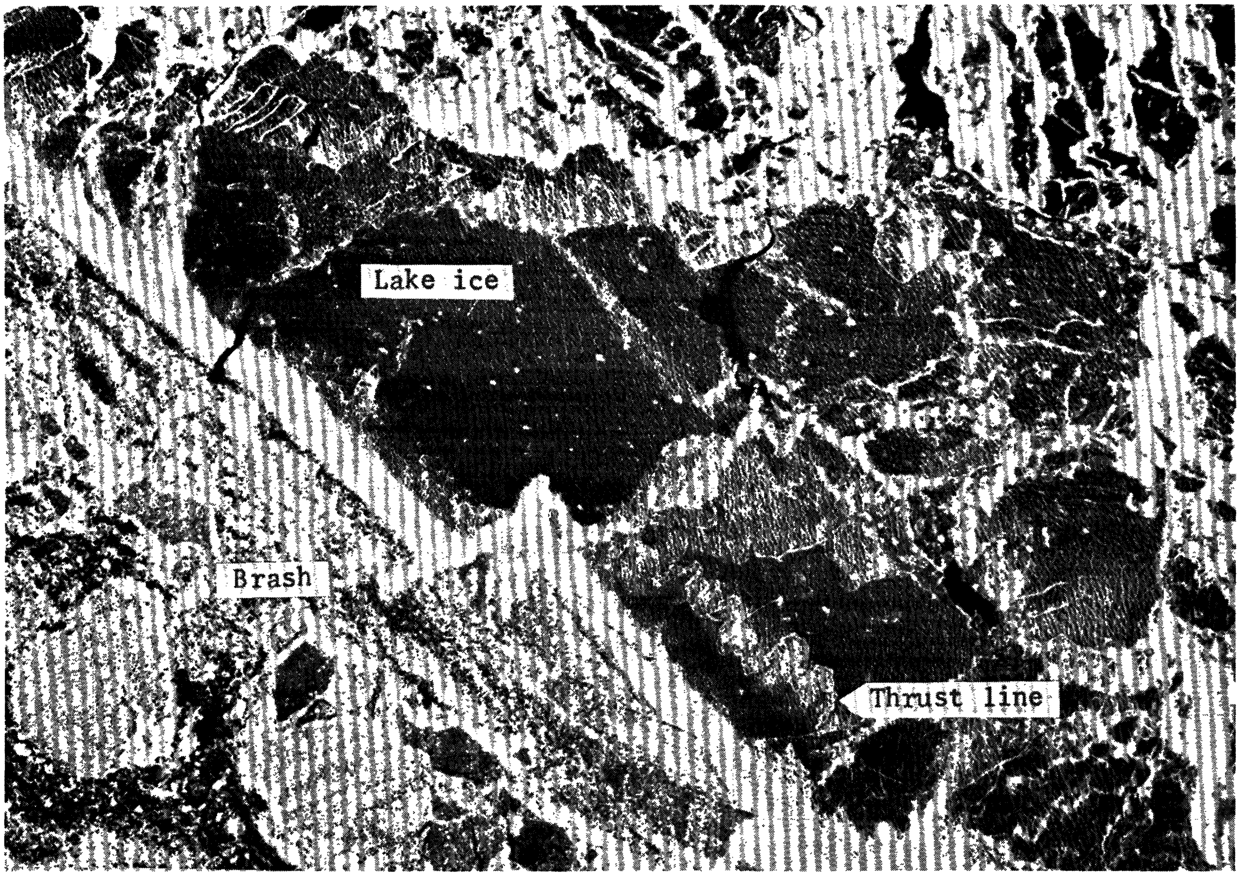

FIG. 53. COMPLEX CRACK PATTERN CAUSED BY WAVE ACTION. This pattern is caused by wave action flexing a drifting ice sheet. An ice sheet such as this, which has been heavily flexed, is an abundant source of brash. Lake Erie, Photo 91-385-1L.

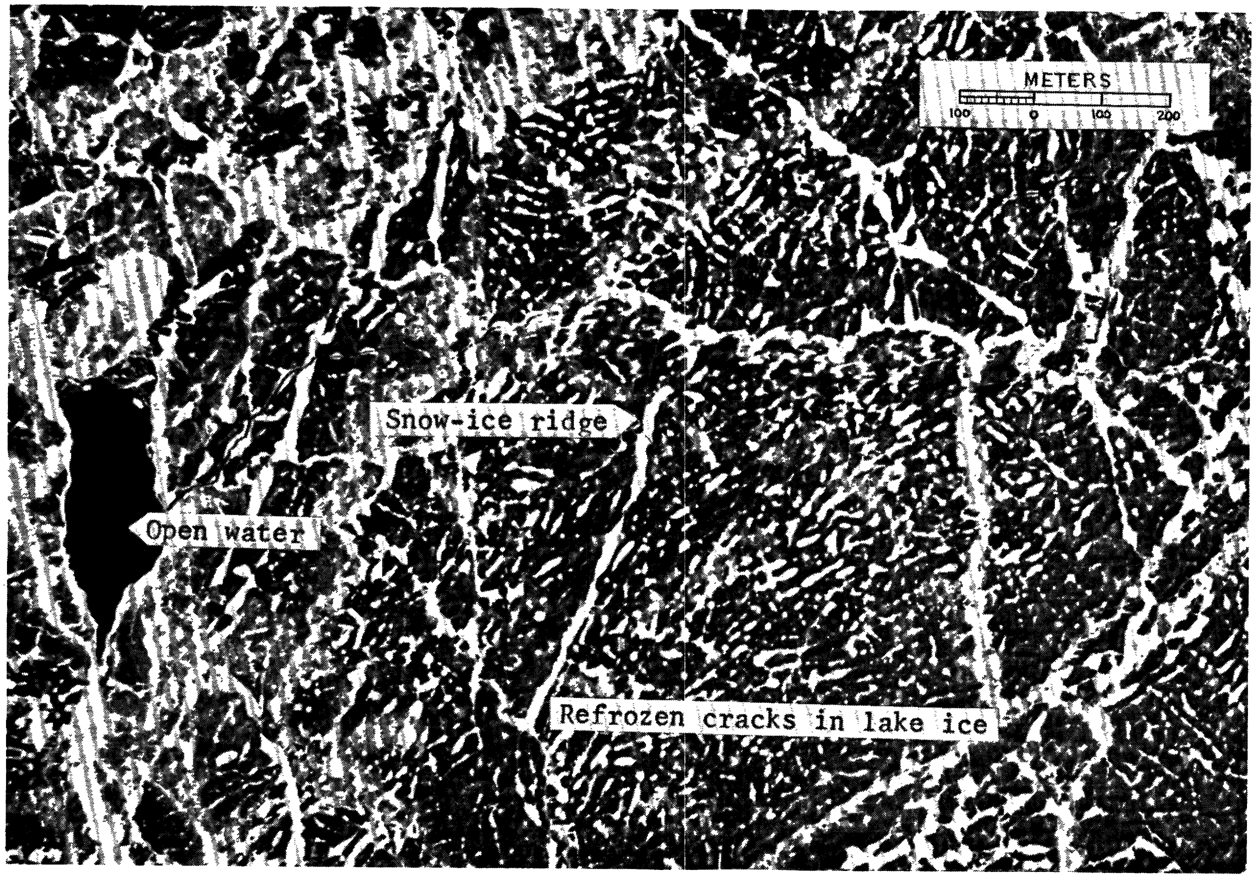

FIG. 54. REFROZEN CRACK PATTERN. This pattern was caused by wave action insufficient to completely fracture and disaggregate the ice sheet. Patterns similar to this were observed in northern Lake Huron in which the fractures had broken up the ice sheet and allowed the individual cakes to drift as a field. Lake Huron, Photo 9R-126-V.

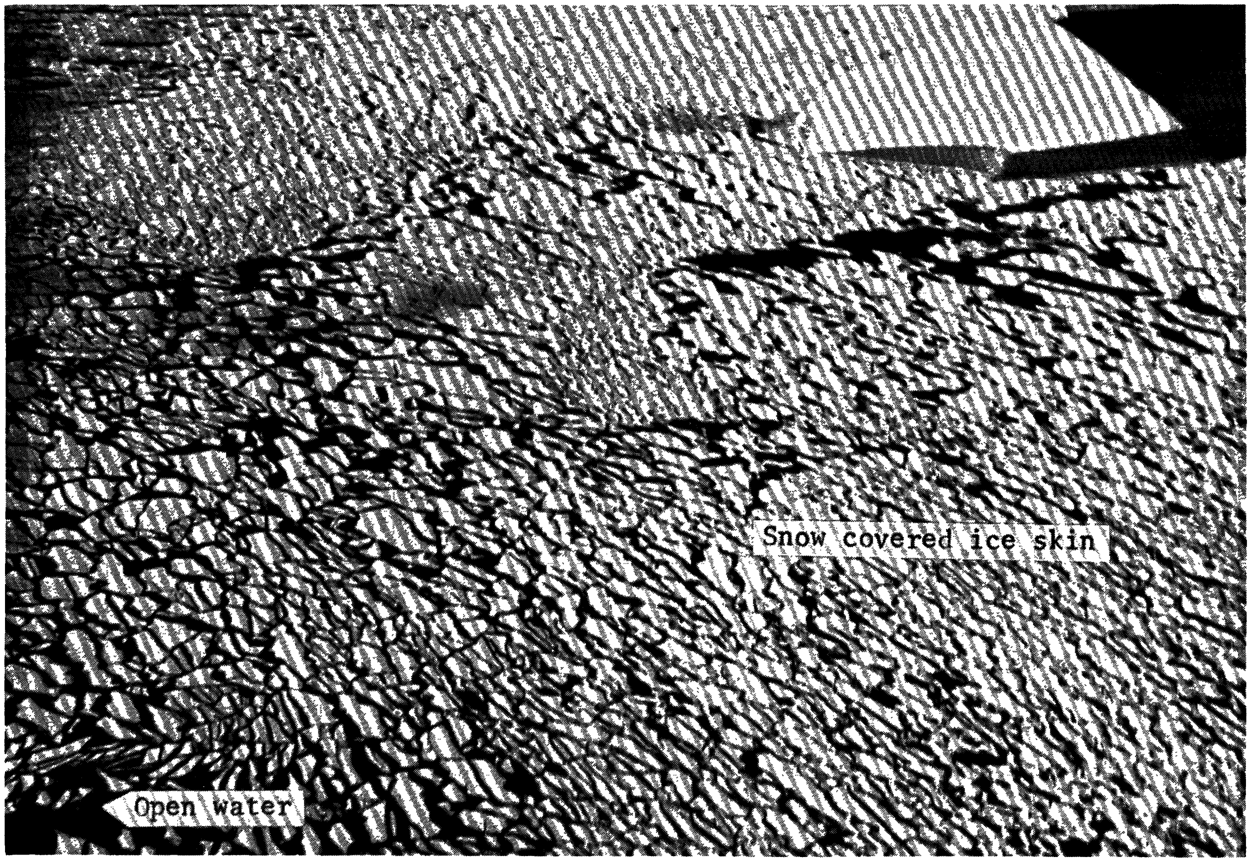

FIG. 55. PHYSICAL BREAK-UP OF A NEWLY FORMED THIN ICE SKIN. This newly formed thin ice skin has been lightly dusted with snow prior to break-up by wave action. This figure, together with Figure 56, illustrates the changes in imagery which can occur resulting from a light snowfall during break-up of an ice sheet. Lake Superior, 1/28/65. Altitude: 1800 ft.

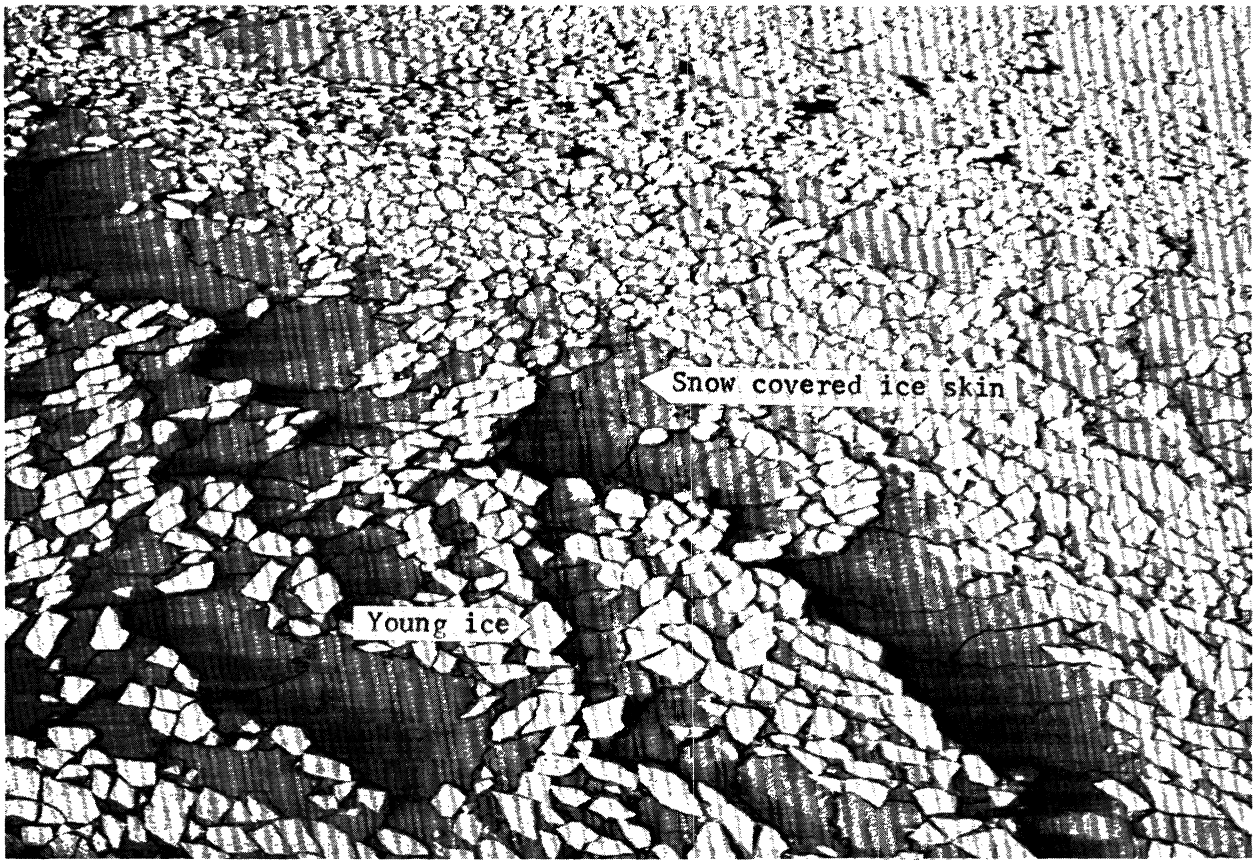

FIG. 56. PHYSICAL BREAK-UP OF A SHEET OF YOUNG ICE. In this case a sheet of young ice has been broken up by wave action and a new ice skin has later formed between the fragments. The area was then mantled by a light dusting of snow. Thrust lines and cracks in the newly formed ice skin are outlined in black where lake waters have soaked into the snow. Lake Michigan, 1/14/65. Altitude: 1500 ft.

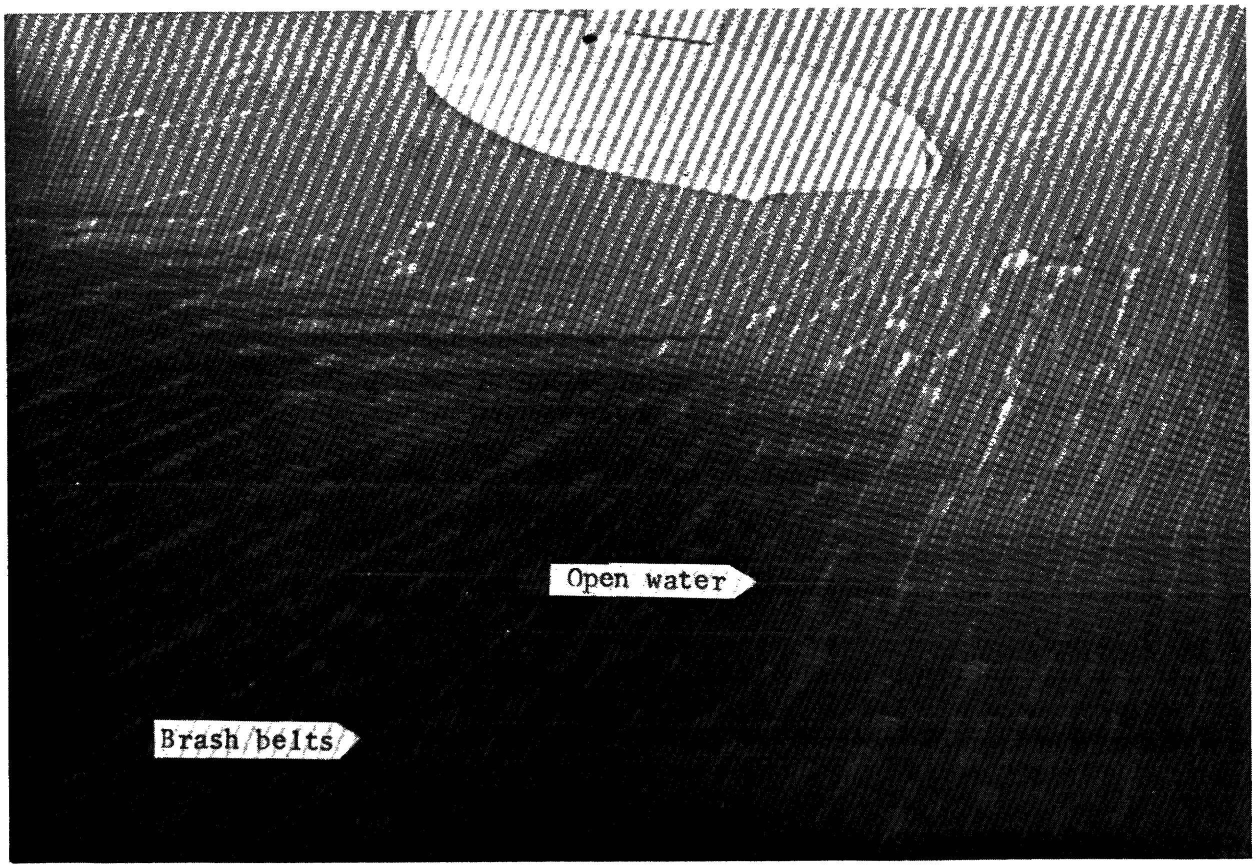

FIG. 57. FIELDS OF BRASH BELTS. These fields are composed of many subparallel brash belts. The basic unit in the belt is the patch, streamlined to varying degrees and streaming a very narrow belt of brash behind it. Some patches were observed to contain small ice floes in the process of breaking up. As these patches drifted before the wind they gradually exhausted the supply of brash and became extremely narrow belts a few meters to tens of meters in width. On a flight over Lake Huron and one passing from the western to the central basin of Lake Erie, all stages in the break-up of the ice sheet were observed. This process included the break-up of ice fields into floes and finally into brash. Lake Huron, 2/5/65. Altitude: 3000 ft.

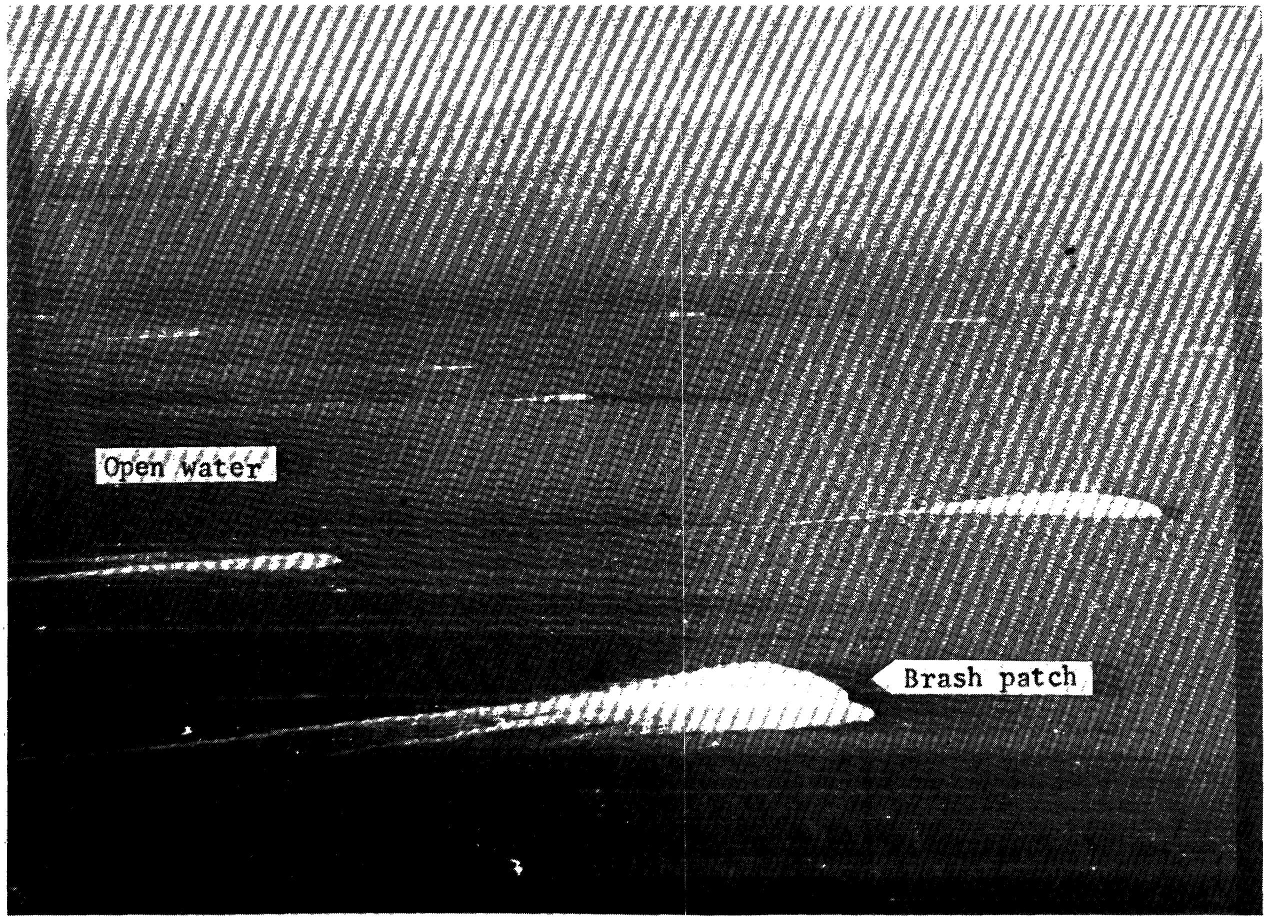

FIG. 58. BRASH PATCH. These isolated, tear-drop shaped brash patches are oriented into the wind. The front of the patch varies from rounded to subrounded to blunt. The shape of the brash patch varies with the wind velocity. The blunter forms are in in equilibrium with the wind velocity. A splitting process is one method by which this equilibrium is achieved. The indentation on the edge of the patch in the foreground is the beginning of such a process. Lake Erie, 1/21/65. Altitude: 2500 ft.

SNOW AND WIND FEATURES

Snowfall and the effects of wind modify the imagery of Great Lakes ice sheets. Sudden changes in albedo result when the dark toned images of lake ice sheets are covered by new snowfall.

The intense, localized snowfall from snow squalls produces extremely distinct serrate lines of demarcation between the new snowfall and bare ice areas or areas of old snow (Figs. 59, 60).

Blowing snows can produce a heightened three-dimensional effect on irregularities in the ice sheet by deposition of snow on the windward surface (Fig. 61) or by the formation of linear dunes (Fig. 62). Snow dunes are formed in patterns (crescentic, linear, or irregular) which contrast sharply with the dark-toned lake ice (Figs. 63, 64).

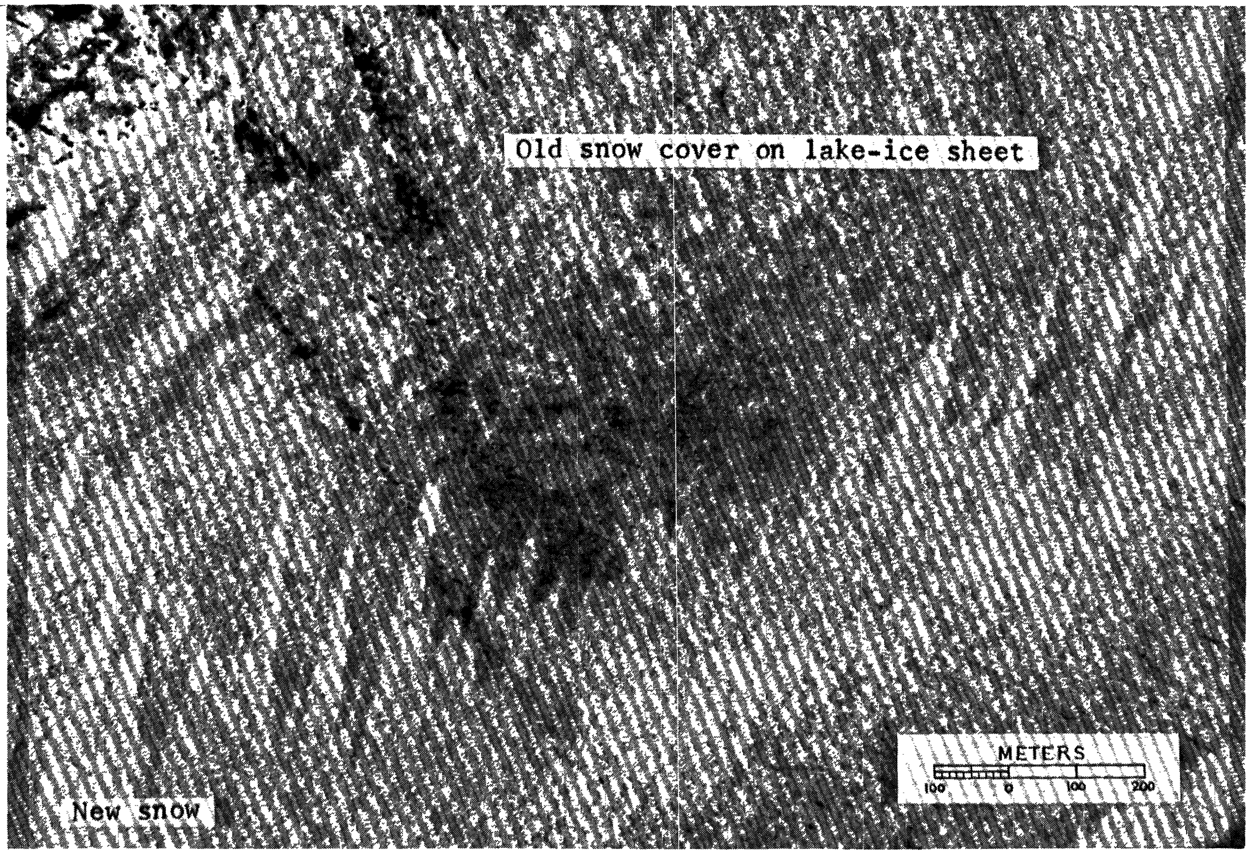

FIG. 59. SNOW SQUALL DEPOSIT. The higher albedo in the lower half of the photograph distinguishes the new from the older snows. The serrate line of demarcation is a depositional feature of the sudden intense snowfall associated with winter squalls. The pattern of snowfall in these winter squalls is somewhat similar to the sharp demarcations between wet and dry areas resulting from summer line squalls. Lake Erie, Photo 9R-461-V.

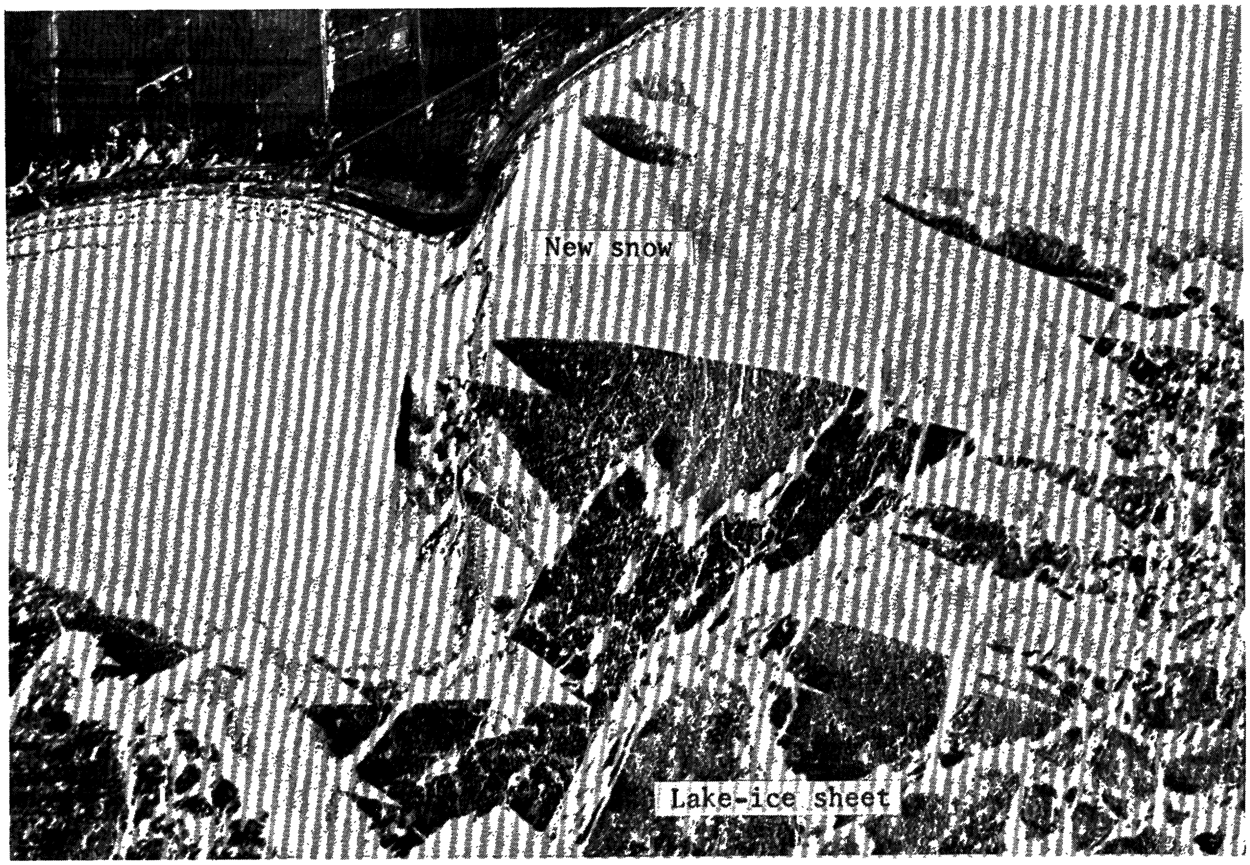

FIG. 60. SNOW SQUALL DEPOSIT. The depositional effects of winter snow squalls are strikingly revealed on the sheet of lake ice. Evidence that the sharp boundaries are depositional is supported by the fact that the boundaries remain clear cut across the pressure ridges. If the snow boundaries were wind scour features, they would be modified by the irregularities of the pressure ridges. A normal fall of snow masks portions of squall features in the upper right. Lake Erie (northern shore), Photo 9L-453-2L.

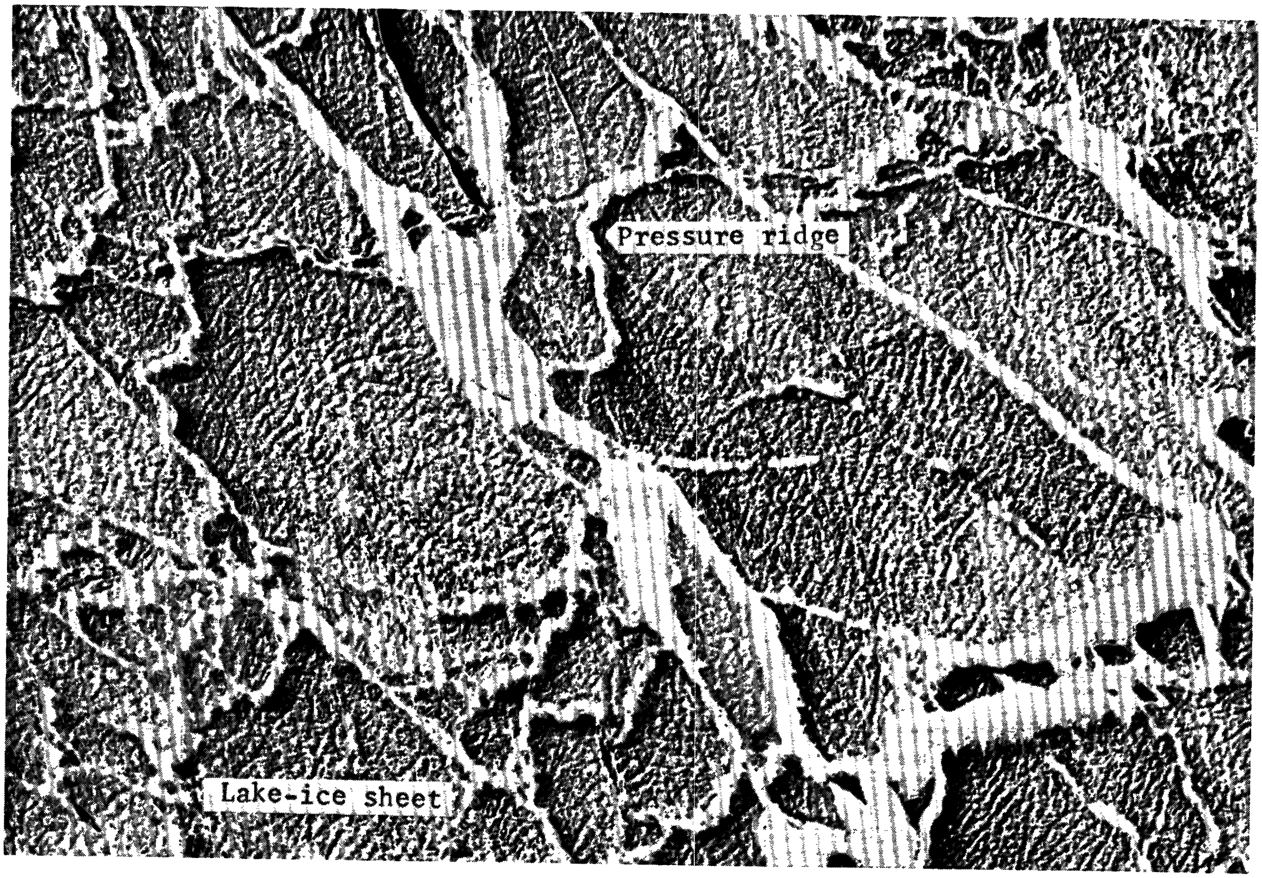

FIG. 61. SHADOWING EFFECT OF A LIGHT SNOWFALL ON SURFACE IRREGULARITIES. A very light snowfall accompanied by a gentle wind has shadowed irregularities on the surface of the ice sheet. Lake Erie, Photo 9L-446-V.

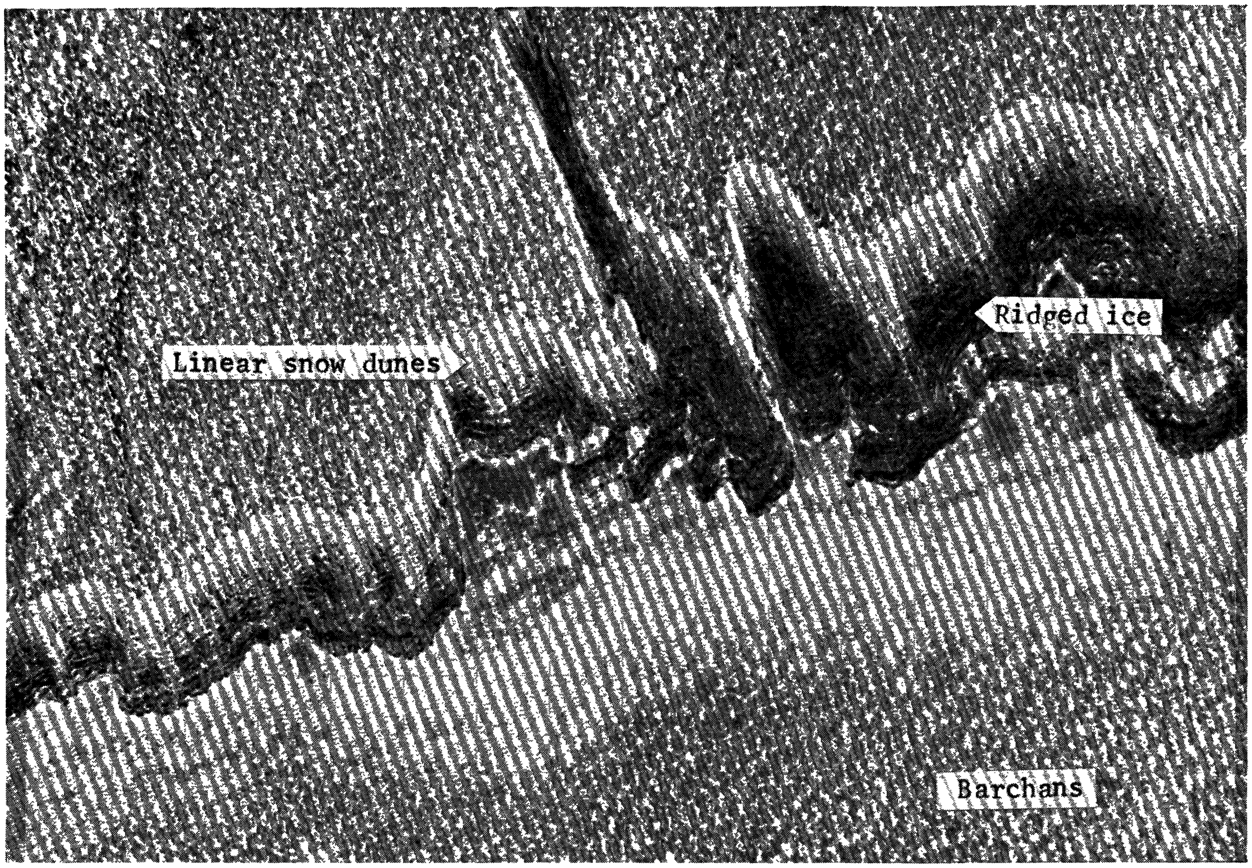

FIG. 62. SHADOWING EFFECT PRODUCED BY LINEAR SNOW DUNES. A unique cliffed appearance is produced on the ice surface by the shadowing effect of linear snow dunes formed in the lee of a pressure ridge. The effect is heightened by the parallelism of the darker ridged ice and the lighter toned linear dunes. Lake Erie, Photo 9L-487-1R.

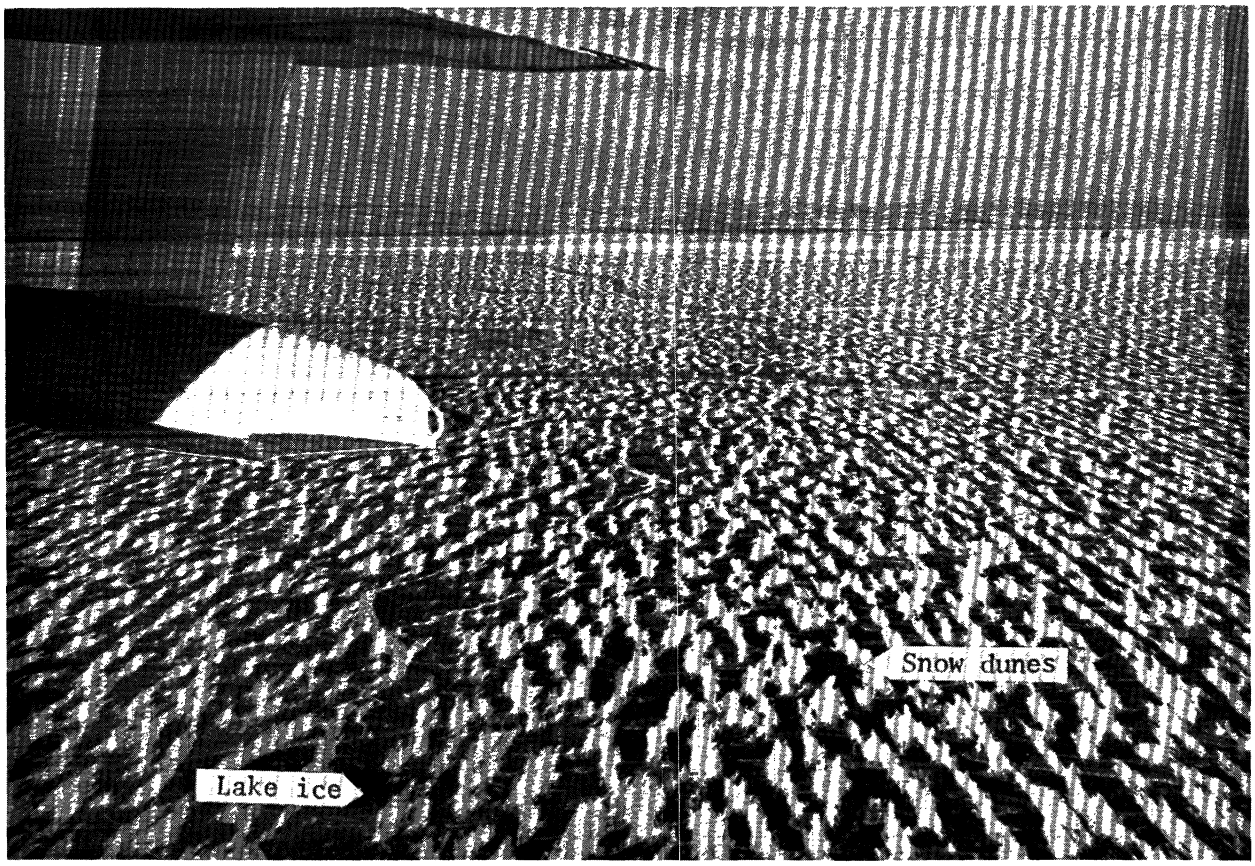

FIG. 63. IRREGULAR SNOW DUNES ON A LAKE-ICE SHEET. Wind-blown snow migrating across the ice sheet has formed an irregular dune pattern. Lake Michigan (Sturgeon Bay area. Wis.) 1/14/65. Altitude: 800 ft.

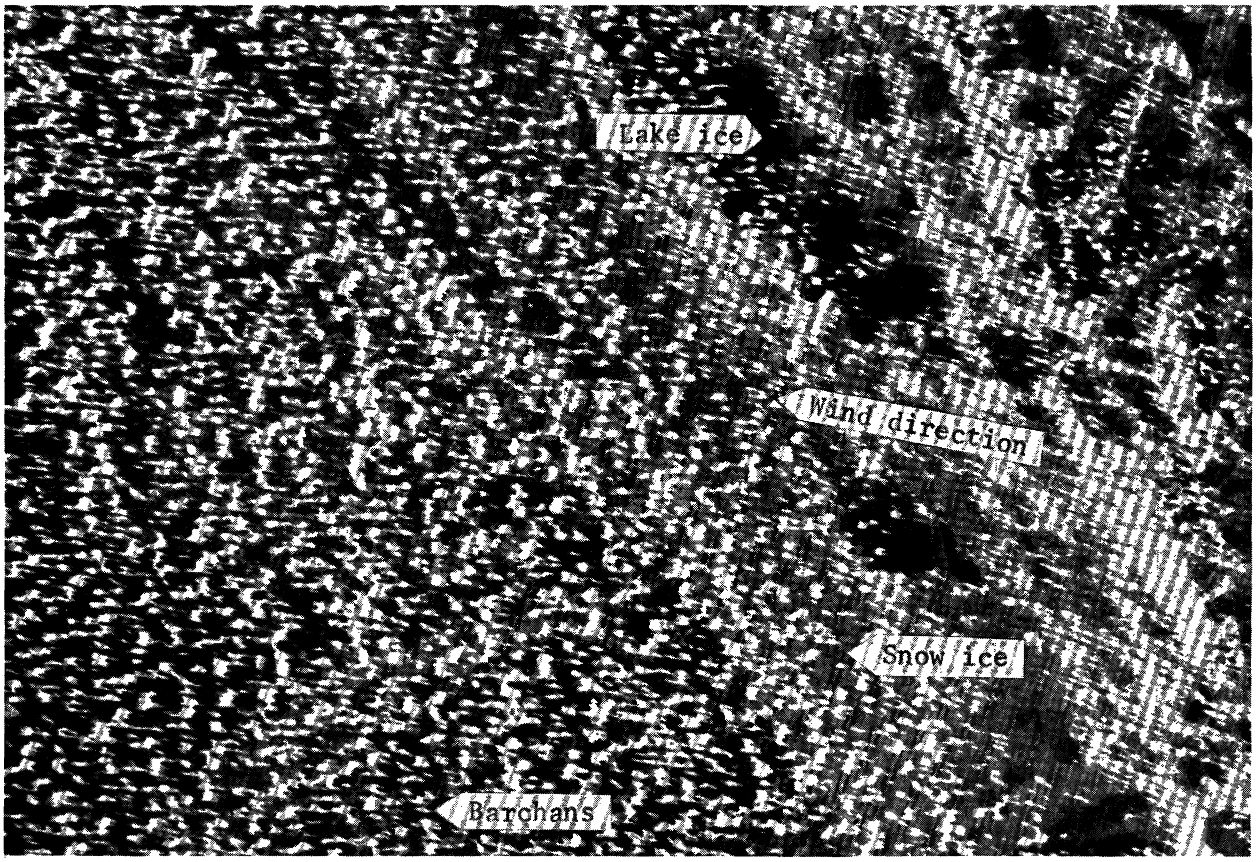

FIG. 64. BARCHANS ON A LAKE-ICE SHEET SURFACE. These crescent-shaped snow dunes are oriented with the horns pointing away from the prevailing wind direction. This form of dune migrates by snow grains advancing up the gentle foreslope and depositing on the steep backslope. In the right of the photo, irregularities on the ice surface cause linear dunes to form. Lake Huron, Photo 9R-105-1L.

SUMMARY

1. Wind Effects

Wind is one of the most important factors affecting Great Lakes ice conditions. Wind determines the patterns observed in slush and frazil ice skims during freeze-up; it induces waves and ground swells causing crack patterns in the ice sheet and thus influences the size and shape of brash. Wind continually breaks up newly formed ice sheets and sweeps the ice away, thus delaying or preventing large portions of the lake from forming an ice cover.

Wind plays the significant role in forming patterns observed in frazil ice skims and slush layers. These surface patterns freeze and remain in the ice sheet during the winter. During ice formation there are usually varying amounts of slush and frazil ice on the water surface, but patterns have been observed when one or the other predominated. During frazil ice formation, winds produce a streaked appearance on the water surface. Once the frazil ice skim has formed, the wind often causes ragged tear lines within the ice skim allowing patches to become detached from the field.

The wind effects on slush layers range from slight folded or festoon-like patterns to intricately stirred ones. The wind also produces triangular "blow-outs" where slush and/or frazil ice have been pushed before the wind. Curded patterns occur where thick slush layers have been sheared by the wind. Ball ice forms in areas of extreme water turbulence.

Wind and the resulting water turbulence determine the crack patterns observed in ice sheets and the size and shape of the resulting brash ice. Ground swells form long parallel crack systems where they work on the edge of fast ice. Drifting ice sheets may be stressed from several directions by waves and ground swells and result in complex intersecting crack systems. The drift of the pack ice sets up compressive forces within the ice floes which result in shear lines and pressure ridges.

Winds are constantly breaking up the sheets of young ice, whereas without this constant physical break-up a thick ice sheet would form. The winds sweep the surface clear of broken ice, recycling it into the ice formation process or causing it to drift into shore zones where it freezes to become part of the fast ice or icefoot.

Winds also cause brash to form into long belts composed of a series of uniquely streamlined brash patches.

2. Snowfall Effects

Snowfall plays a significant role in determining the structure and albedo of Great Lakes ice sheets. In these respects the time and the distribution of the snowfall is more important than the yearly total.

If the snow falls on a quiet water surface the slush freezes and forms a granular snow-ice layer. Lake ice columnar in structure accretes under the surface layer, forming a compound-structure ice sheet.

The structure of the ice sheet is also dependent upon wind and water turbulence. If there is a steady wind pressure on a thick slush layer, shearing occurs, producing a uniquely curded pattern. A thin layer of slush on the water surface is slightly to intricately folded by gentle to moderate water turbulence. Fields of ball ice form an ice sheet conglomeratic in structure. Snow-ice patterns resulting from turbulence can form at any time during the winter because of the recurring snowfalls over the extensive areas of open water.

Snowfalls can also cause rapid changes in the albedo of ice sheet imagery.

Linear and crescent shaped dunes result from the deposition of blowing snow on the ice sheet surface. Snow-ice mounds and ridges form along breaks in the ice sheet.

The total amount of snowfall becomes significant in the bays and coves where fast ice forms. Here the weight of the snows depresses the ice sheet, causing lake waters to soak into the snowpack and begin the formation of snow ice. These bays and coves are thus transitional in ice structure between the types of ice sheets formed on the Great Lakes proper and inland lakes.

3. Prediction of Ice Conditions

Observations made on the ice reconnaissance flights suggest that each lake or area within a lake has a given range of ice types and a general sequence of patterns from freeze-up to break-up. Sequences of aerial photographs could establish these patterns.

Certain ice conditions may also occur as annual features due to the result of shoreline configuration and prevailing winds and currents. As a result of prevailing southwest winds over Lake Erie, zones of heavily pressured ice occurred on the west side of Long Point, Ontario while open water was often observed on the east side. Extensive storm-icefoot development was observed on the south shore of Lake Erie, resulting from the northerly storm winds.

Sharp delineations were observed in the presence or absence of wide zones or brash along the shoreline of the Upper Peninsula as a result of shorelines lying in the lee of the Keweenaw Peninsula. The Peninsula protected the shoreline from the southeasterly drift of brash resulting from the break-up of ice sheets formed on the main body of Lake Superior.

4. Albedo of Lake Ice

The albedo of newly formed ice skim or that of young ice is extremely low. On aerial photographs these black toned areas are often difficult to distinguish from areas of open water.

The albedo of the ice sheet increases by internal and external processes. Internal processes include the results of compressive forces on the pack which form pressure ridges and thrusts, the results of cracking induced by ground swells, and the effects of solar radiation resulting in crystal boundary melting and internal liquefaction at the time of break-up. External processes include dune accumulations of blowing snow, snow-ice formation along cracks in the ice sheet, and new snowfalls.

5. Thrust Features

The present study indicates that the pattern of thrust can be related in a general way to ice thickness. Thrust patterns in a frazil ice skim are characterized by a jagged thrust line where individual thrust units are irregular and poorly defined. The felt-like frazil ice skim is structurally incompetent to transmit the forces. Thrust patterns in harder and thicker ice sheets are characterized by clearly defined rectilinear thrust units.

The rectilinear pattern was observed not only in young ice sheets but those surfaced with snow ice and in ice sheets composed of refrozen brash. The width of the thrust units increased with ice sheet thickness. Thrust lines up to 14 kilometers in length were observed in refrozen leads. The widths of individual rectilinear thrust units ranged from approximately 33 to 220 meters while the length of overthrust extended up to 412 meters.

These thrust features are generally similar to features reported in new sea ice. These observations indicate that the presence of a lubricating brine film between thrust plates is not necessary (as thought in sea ice) to explain the unusual length of overthrust.

6. Contrast Between Ice Formation on Inland Lakes and the Great Lakes

The formation of an ice sheet of an inland lake is essentially a static process where the stages of nucleation, accretion, and break-up are well defined and of limited duration. In the Great Lakes, ice formation is a dynamic process where within a given drifting ice pack all three of these processes may be going on simultaneously.

7. Geologic Effects

Geologic effects result directly from various lake ice formations. The formation of an icefoot protects the normal shoreline from wave erosion for periods of months, as well as shifting the zone of scour toward deeper water.

Ball ice accretion in nearshore zones often includes sand thrown into suspension by water turbulence. The drift of the ball transports sand along the coast and to offshore sites.

An ice cover serves as a platform upon which airborne dusts are deposited. Surface colorations resulting from wind-blown dusts from open fields were observed on ice floes along the north shore of Lake Erie.

The stratigraphy of bottom sediments is also affected by the presence and the duration of an ice cover. The ice sheet eliminates water turbulence for varying lengths of time and allows suspended sediment to settle.

Ice ramparts are also often formed along the shorelines by the action of wind-driven ice floes overriding the beaches.

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APPENDIX I.

RECOMMENDATIONS FOR FUTURE RESEARCH

These recommendations for future research are based on the examination of aerial photography, observations made on ice reconnaissance flights, and the writer's previous experience. The recommendations are in three parts; 1) problems which merit study connected with ice conditions, 2) methods of ice reconnaissance, and 3) lake ice problems for investigation by infrared imagery.

ICE CONDITIONS

Freeze-up Period

1. Patterns in snow-ice sheet. The effect of the distribution of snowfall on the surface patterns and the structure of the initial snow-ice sheet needs further study.

2. Frazil ice formation. The imagery of frazil ice formation needs to be traced from its initial appearance to its consolidation into a hard ice skin.

3. Icefoot formation. Studies of icefoot formation should include the time and conditions for formation, structure, width, distribution of icefoot types in relation to shoreline characteristics, and the effects on shoreline processes.

Accretion

1. Fast ice. Little is known concerning the distribution of fast ice in the Great Lakes. Observations are needed on the location, time of formation, thickness, structure, albedo and duration.

2. Crystal size and orientation. Information is lacking on the size and orientation of crystals which accrete under wind-stirred patterns in the slush and frazil ice skims. This crystal structure may be quite different from that formed under the more static conditions found in inland lakes.

3. Structural types of ice sheets. The distribution of the various structural types of lake ice sheets needs to be determined by season. This would include such ice types as the simple- and compound-structure ice sheet, ball ice sheet, brash sheets, etc.

Break-up

1. Albedo changes. Changes in ice albedo with the approach of break-up needs to be related to changes in the structure of the ice resulting from crystal boundary melting (candling) and internal liquefaction. The writer believes that the recognition of these subtle albedo changes in the various types of ice sheet is the critical parameter in the prediction of break-up from visual imagery.

2. Thrust structures. The various patterns of thrusting need to be related more closely to ice sheet thickness. Patterns of thrusting need to be traced from the distinct rectilinear patterns observed in thin ice sheets to the pressure ridged patterns of thick ice sheets.

General

1. Annual features. The location of annual features within a lake need to be charted. These include open leads, open water, fast ice, areas of icefoot formation, areas of brash, polynyas, and ice generating areas.

2. Structure of ice pack. Visual imagery is critically needed to view the overall structure of the Great Lakes Ice Pack. Points for investigation include first the identification of the various classes of ice composing the ice cover. With this information, the structure, location, areal coverage, concentration, and imagery of each class of ice should be traced from the freeze-up to the break-up. Studies are also needed on the progressive changes that take place in a drifting ice pack in terms of the distribution of ice types, size and shape of floes, concentration, and the direction and rate of drift.

3. Contamination in ice floes. The freezing of lake waters contaminated by chemical and organic wastes forms ice rafts of contamination which may drift into uncontaminated areas. Studies are needed to evaluate this situation! Attention should be given to the rate at which the contaminants are released during the comminution by ice floe abrasion and by ice sheet melting during the spring break-up.

4. Ice terminology. The terminology now in use is the accumulation of terms used in surface navigation and in aerial reconnaissance over polar sea ice. The terms are useful in a general way to describe Great Lakes ice conditions. In many cases new terms are needed and in other cases older terms need to be redefined. A review of the terminology is essential to the proper training of future ice observers.

5. Illustrated glossaries. Two publications are needed to further Great Lakes ice research. The most pressing is the publication of a compact glossary illustrated with photographs of Great Lakes ice features for the use of ice observers.

During the next two winters a comprehensive, illustrated guide to Great Lakes ice processes and features should be assembled. The writer's present report should be considered as an initial step in this direction.

6. Annotated bibliography. At this stage of Great Lakes ice research an annotated bibliography on all facets of the problem should be compiled by interested investigators. This publication should include such subjects as heat budgets of the lakes, winter currents, distribution of snowfall, direction and velocity of prevailing winds, areas of unusual lake turbulence and lake ice conditions.

This bibliography should also include a review of the Scandinavian literature on freshwater ice sheets on the Baltic Sea as well as Soviet ice investigations on their large inland lakes.

7. Catalog of air photo coverage. A catalog needs to be compiled of air photo coverage of Great Lakes ice conditions held in U. S. Department of Defense and Canadian Government files.

8. Status of Great Lakes ice research. A review is needed of the Canadian and American literature on Great Lakes ice conditions as well as a survey of current projects. A three- to five-year Canadian-American program for Great Lakes ice research is needed at this time.

ICE RECONNAISSANCE METHODS

Ice Reconnaissance Flights

The present U. S. studies on Great Lakes ice distribution are based primarily on ice reconnaissance flights. These flights are flown by the U. S. Coast Guard and manned by observers supplied by the U. S. Lake Survey, Corps of Engineers. Reconnaissance flights are supplemented on occasion by aerial photography of selected areas flown by the U. S. Air Force. The purpose of these studies is to provide information on ice cover which, when correlated with meteorological parameters, will provide a guide for forecasting the ice conditions for shipping.

The U. S. ice reconnaissance flights are made over the various Great Lakes at approximately biweekly intervals between the period of initial ice formation and break-up and result in the publication of ice charts (Scales: 25-40 miles to the inch) by the Lake Survey. These ice charts are based on notes taken while flying at altitudes from lake level up to 3000-4000 ft in a HU-16E Grumman Albatross at speeds at 155 knots. The ice charts provide a generalized picture of ice distribution.

Based on 30 hours of flight time on reconnaissance flights over the Great Lakes during January and February 1965, the writer believes that certain changes are needed in order to further improve the quality of the ice charts as well as to make more effective use of the flight time.

The following is recommended:

1. Reconnaissance flights at higher altitudes. This is based on the scale of the ice charts and the generalized method of representing ice types and their distribution. At present flight altitudes, too much detail passes the observers for any true perspective of the overall distribution of ice types. Ice observers could be further trained for pattern recognition of the basic ice types from higher altitudes. At these altitudes the major structural features and patterns of ice distribution could be seen in better perspective. The writer recognizes that winter weather conditions often determine a flight altitude which is other than optimum.

2. Use of faster aircraft. The present airspeeds of approximately 155 knots seriously limit the coverage that can be obtained during the brief periods of clear weather in the winter. At these speeds a reconnaissance down the south shore of Lake Erie and back the north shore requires about 6 hours. In the case of larger lakes, adequate coverage is not being provided by current methods. To obtain anywhere near adequate coverage of the larger lakes would require several days of flying time. When this time requirement is coupled with the variable winter weather conditions, needs for crew rest, and returns to base for fuel and maintenance, reconnaissance of the larger lakes becomes nearly impossible without impracticable expenditures of time. A faster, higher flying aircraft is needed to take advantage of the 1-2 day breaks in the weather.

3. Ice reconnaissance methods for use in the Great Lakes should be further reviewed and evaluated. Current ice reconnaissance methods are based on procedures developed for sea ice reconnaissance along Arctic and Antarctic shipping routes and in many cases do not fit the ice problems of the Great Lakes.

Aerial Photography

The role of aerial photography in the study of Great Lakes ice conditions is presently limited to occasional flights over selected areas. The present understanding of Great Lakes ice distribution is based principally on subjective information of a reconnaissance nature. If a fuller understanding is to be obtained of the distribution and the drift of the various ice types, extensive aerial imagery will have to be used. In present U.S. programs in Great Lakes ice studies, little research or operational use has been made of current technology in aerial photography. Each winter's delay in not obtaining sequences of visual imagery of the ice conditions is a loss of critical data.

Aerial photography could serve two functions in Great Lakes ice research. 1) Very high altitude photographs could serve as a rapid reconnaissance method complementing current reconnaissance flights. A permanent photographic record would thus be obtained which would

provide a basis for study of ice types and their distribution. The interpretation of ice photography flown from very high altitudes would aid in the interpretation of high resolution ice imagery to be available in the near future from satellite coverage. 2) Low and medium altitude aerial photography would provide a body of Great Lakes ice imagery for research use. Studies are needed to classify Great Lakes ice types, their distribution and drift during the winter, and the subtle changes in albedo and imagery which mark the gradual disintegration of the ice and the imminent break-up.

Plans should be made to obtain complete photographic coverage of all lakes several times during the winter plus a plan for detailed coverage of a different lake each year. The collection and interpretation of visual imagery needs to be made to serve as a basis for the interpretation of infrared, radar, and microwave imagery of Great Lakes ice conditions.

Future ice investigations should plan to utilize the latest sensor technology. Parker and Wolff (1965) review the potentialities of the various remote sensors for determining the distribution, thickness, and ice types along major shipping routes.

LAKE ICE PROBLEMS FOR INFRARED IMAGERY

Great Lakes ice imagery is complex, with formation and break-up of the ice sheet going on continuously throughout the winter. A program of infrared investigation of Great Lakes ice would be aided by a preliminary investigation of an inland lake where the stages of ice formation, accretion, and break-up are well defined and where ground control can be easily secured. A study of this type could be carried out on a lake immediately adjacent to the Great Lakes (Lake St. Clair) or in large bays of the Great Lakes such as Green Bay (Lake Michigan).

The stages in ice formation which should be investigated include: lake cooling, ice formation, ice accretion, and the break-up of the ice sheet.

Lake water cooling. Patterns of cooling within the water body would be indicated by changes in the gray tone of the image. Zonal cooling and freezing of the water surface is usually reflected in the crystal structure of the ice sheet.

Ice formation. The imagery of ice formation is complex. In visual imagery, a sequence of patterns appear during frazil ice formation when individual dendrites of ice form on the supercooled water surface and coalesce to form an ice skim. The effects of wind and snow on this frazil ice skim produce a wide variety of patterns.

Another distinct sequence of images results from the effects of wind and water turbulence on slush layers resulting from snowfalls.

Accretion. At the beginning of ice accretion, thin ice skins have a temperature close to the water temperature, $0^{\circ}C$, and could result in indistinct images. As the ice sheet thickens it begins to have a thermal regime of its own, making it possible to determine the relative thickness of the ice sheet. This imagery would be modified by the developing structures of the ice sheet, for example, the distribution of layers of snow ice and/or slush, snow dunes, water streaks, thaw holes, and cracks and structures resulting from pack ice pressures.

The thermal regime of the ice sheet would be further modified by the unique patterns produced by snow squall deposits. Distinctive patterns would also be produced by the effects of blowing snow in forming linear, irregular and crescentic snow dunes.

The progressive changes in imagery of the ice sheet and the features which develop in it could be traced on a lake ice sheet which remains in place throughout the winter. This is in sharp contrast to the partial development which could be observed on the drifting floes of the open lake.

The quantitative measure of the thermal contraction and expansion of an ice sheet could be correlated with changes in the infrared imagery as the sheet cooled and warmed.

Break-up. Physical break-up of the ice sheet could be observed in the complex crack pattern which forms as a result of wave action flexing the ice sheet.

The prediction of the spring break-up might be possible based on the fact that the sheet warms up to $0^{\circ}C$. At temperatures close to this point, the ice sheet becomes a mass of unbonded columnar crystals as the crystal boundaries liquefy. Further changes take place within the crystal as internal liquefaction occurs along the crystallographic plane (001), which leaves the ice sheet in a structurally weakened state.

Indications of the approach of break-up might also be obtained by noting changes in the imagery as the ice sheet thins by bottom melting.

APPENDIX II

GLOSSARY OF TERMS

ALBEDO—The measure of the reflectivity of the ice surface. The albedo of a sheet of new lake ice is low whereas that of a new snowfall is high.

BALL ICE—Roughly spherical masses of slush and frazil ice which accrete in turbulent waters found in nearshore and offshore environments. In the Great Lakes, observed diameters range from several centimeters to approximately 2 meters. Fields of floating ball ice freeze into uniquely structured ice sheets.

BARCHANS—Crescent shaped snow dunes which form with the horns of the crescent pointing away from the prevailing wind direction.

BELTS—A relatively narrow band of fragments of floating ice of any concentration.

BRASH—Small fragments of lake, river, or sea ice less than 2 meters in diameter.

CANDLING—The process by which the bonding between crystals melts and drains away leaving an unbonded aggregate of crystals. This aggregate of crystals is commonly called candle ice.

COMPOUND-STRUCTURE—An ice sheet composed of ice of two or more types, each with a different crystal structure. For example, snow ice (ice formed by the freezing of water soaked snows) may form on lake ice which has columnar structure.

FRAZIL ICE—Dendrites of ice which form on the water surface during freeze-up. These dendrites coalesce to form the initial ice skim.

ICE COVER—The ice layer covering a body of water regardless of its crystal structure.

ICE SKIM—The initial loose, flexible ice layer a few millimeters in thickness, composed of frazil ice crystals.

ICE SKIN—The first film of newly formed ice which has any degree of hardness.

INTERNAL LIQUEFACTION—The process of internal melting along the basal plane of the ice crystal (001) under the influence of heat radiation. This aids in the spring break-up of the ice sheet by honeycombing the crystals.

INTERNAL WAVES—The waves which can occur in stratified water and which are characterized by having the greatest vertical displacement at the boundary surface or some intermediate depth where the amplitude can many times exceed the amplitudes of waves at the surface. Internal waves may explain the distribution belts of ball ice aligned parallel with the shoreline.

LAKE ICE—The columnar structured ice sheet resulting from the freezing of lake waters.

PATCH—An irregular cluster of floating ice fragments of any concentration.

SASTRUGI—Wave-like ridges of snow formed by the scouring action of wind on a snow cover.

SIMPLE STRUCTURE—An ice sheet which is composed of only one ice type, i.e. lake ice or snow ice.

SLUDGE—An accumulation of soft ice mixed with slush.

SLUSH—Water-soaked snow.

SNOW ICE—The ice which forms from the freezing of water-soaked snows. Grain sizes range from fractions of millimeter to 1 cm.

THRUST STRUCTURES—Result when thin sheets of lake ice are brought together by pack pressure. This interaction forms a series of parallel, rectilinear overthrusts alternating with similarly shaped underthrusts.

WATER STREAKS—The term used by the writer for the distinctive serrate pattern formed when films of water are blown out over the ice sheet surface from leads and openings along fracture lines.